Multiband superconductivity in interface superconductors

Jonathan Edge
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- STO and LAO/STO
- Probes for multiband SC
- Multiband signature in H_{c2}
- Results for Hc2 in STO and LAO/STO

NORDITA

JME & A.Balatsky arXiv:1401.5318

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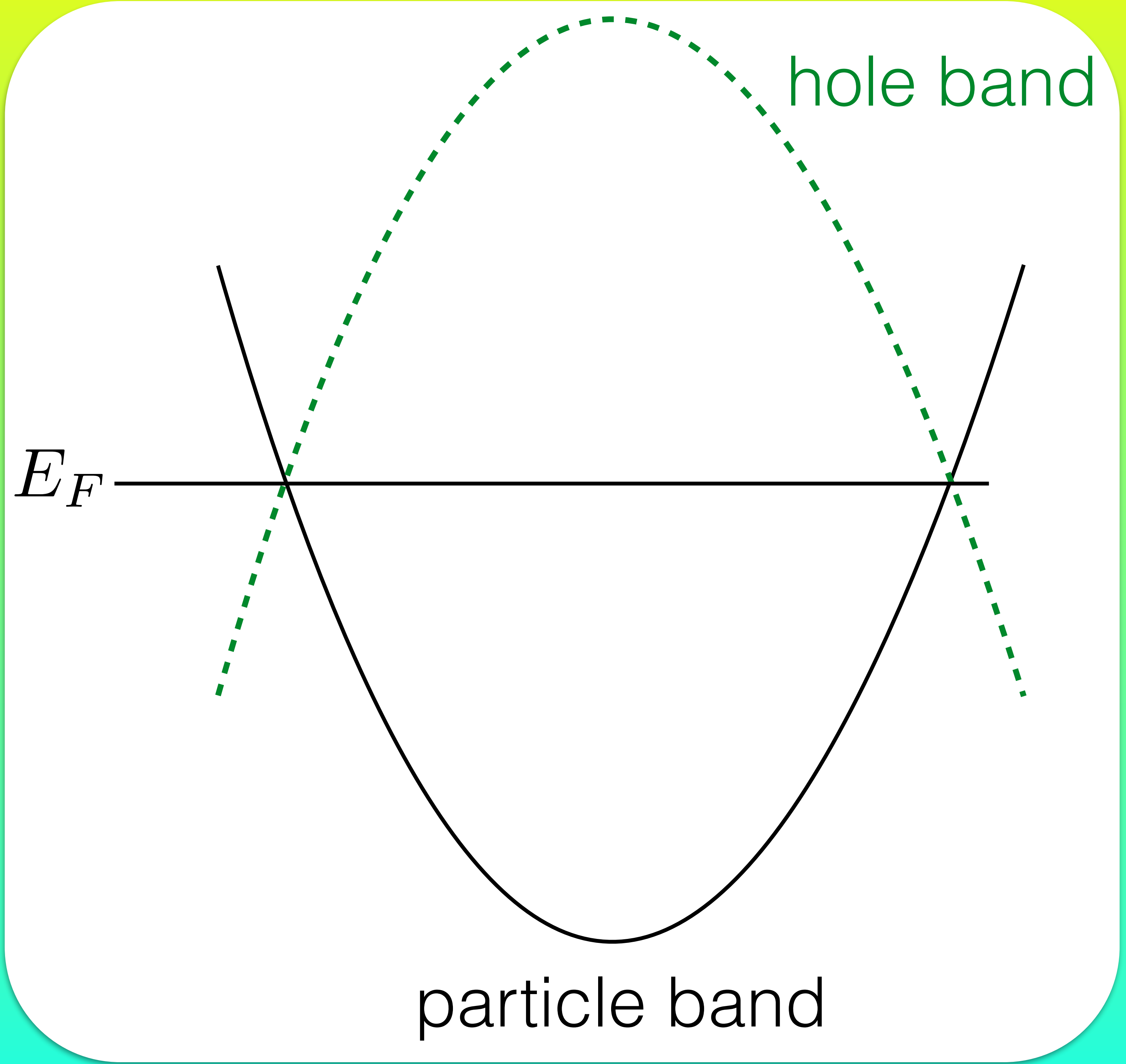
Ordinary single band superconductivity

- One band crossing Fermi energy
- Pairing between opposite sides of the Fermi surface opens a gap Δ in the density of states



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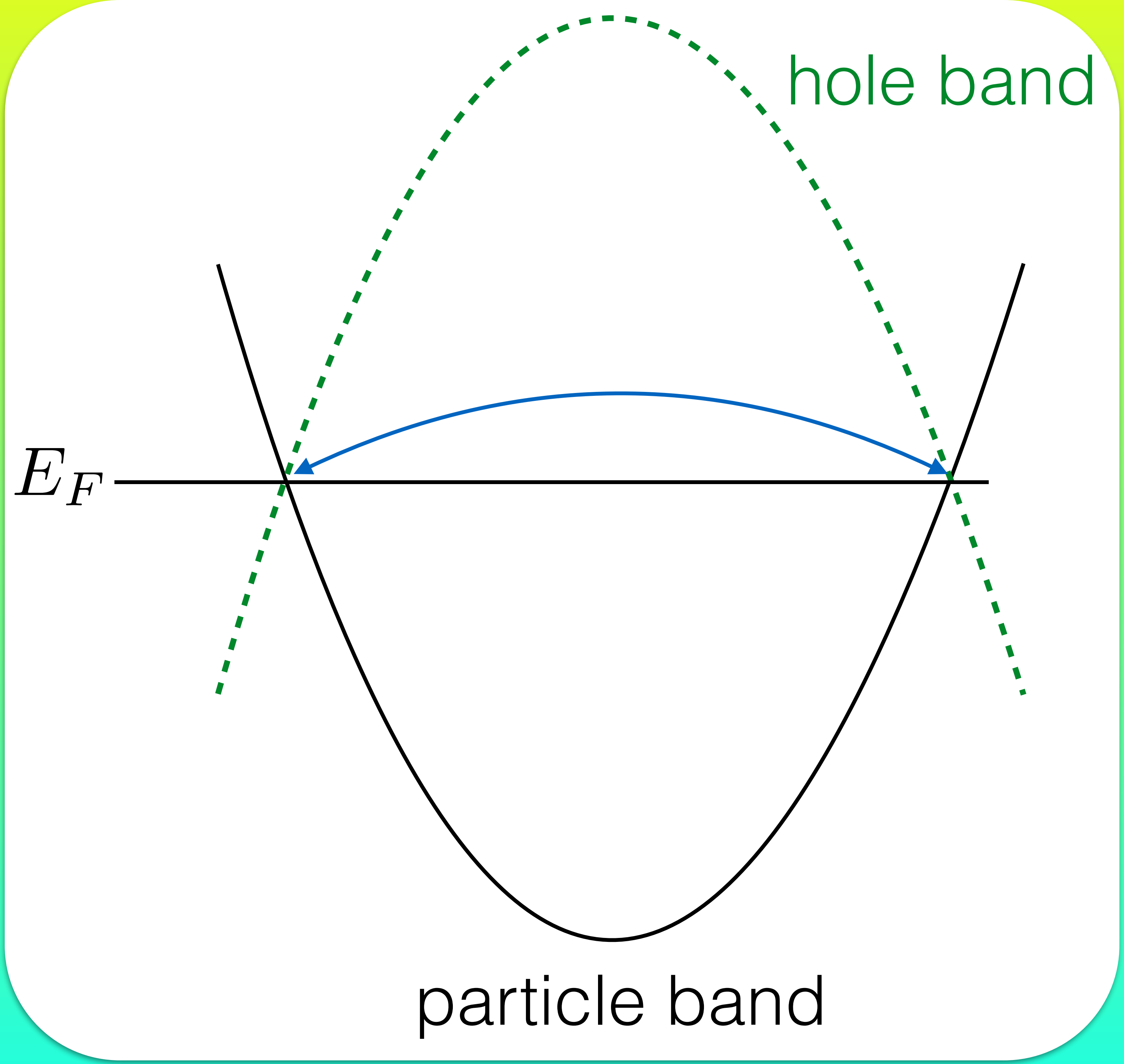

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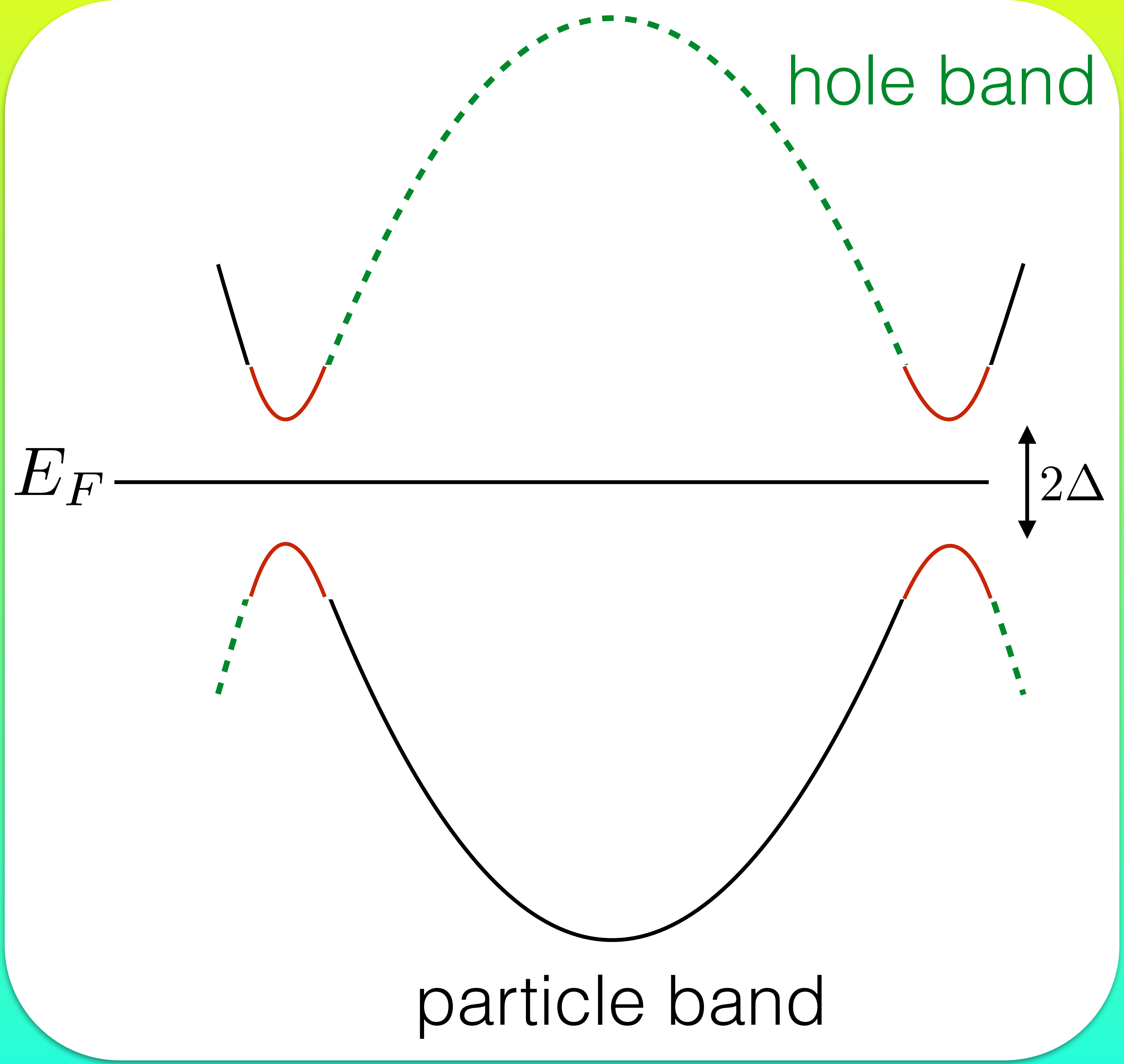
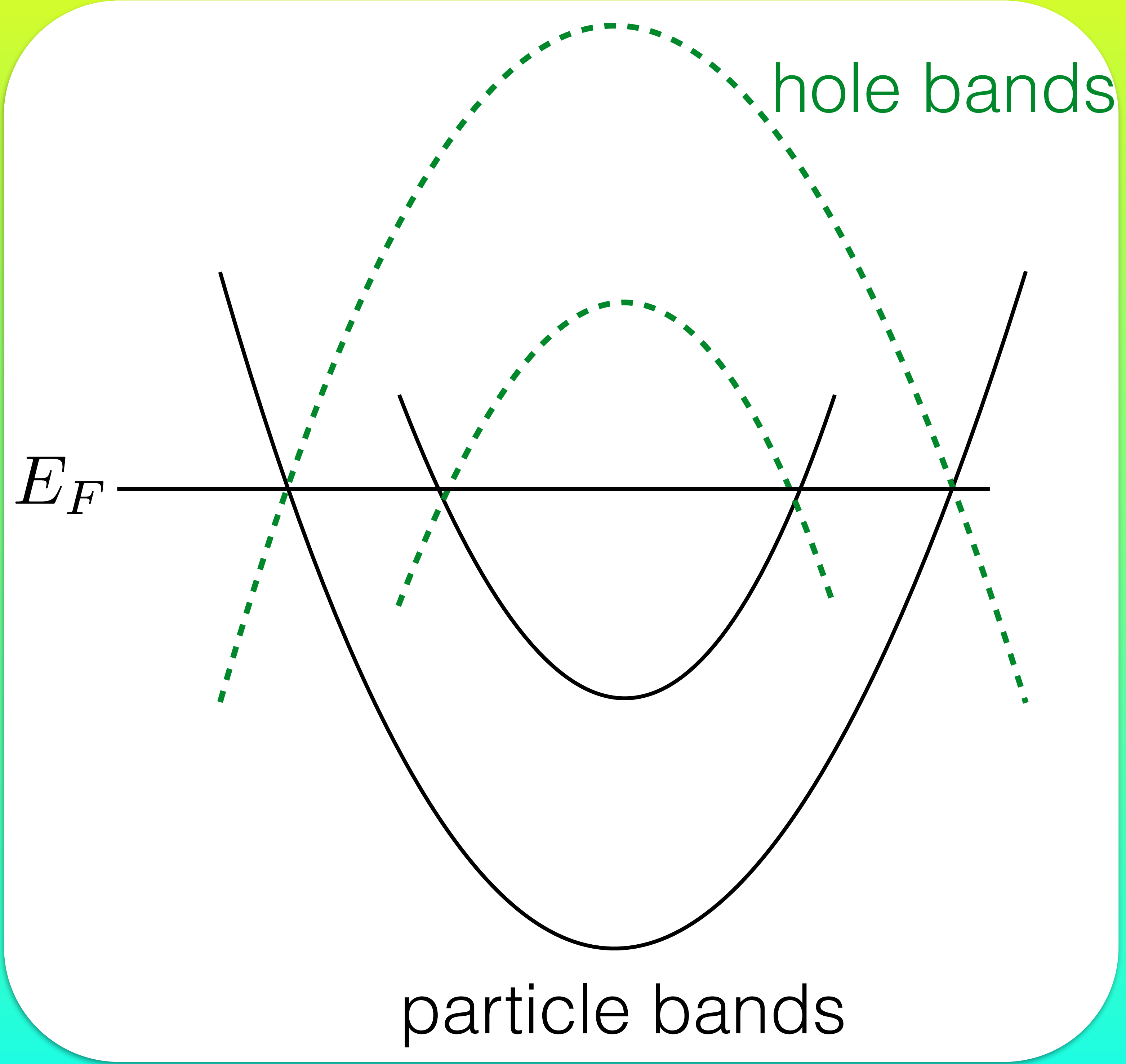


Multiband superconductivity

Suhl, PRL 1959

- Two bands crossing the Fermi energy
- Two (different) gaps Δ open up



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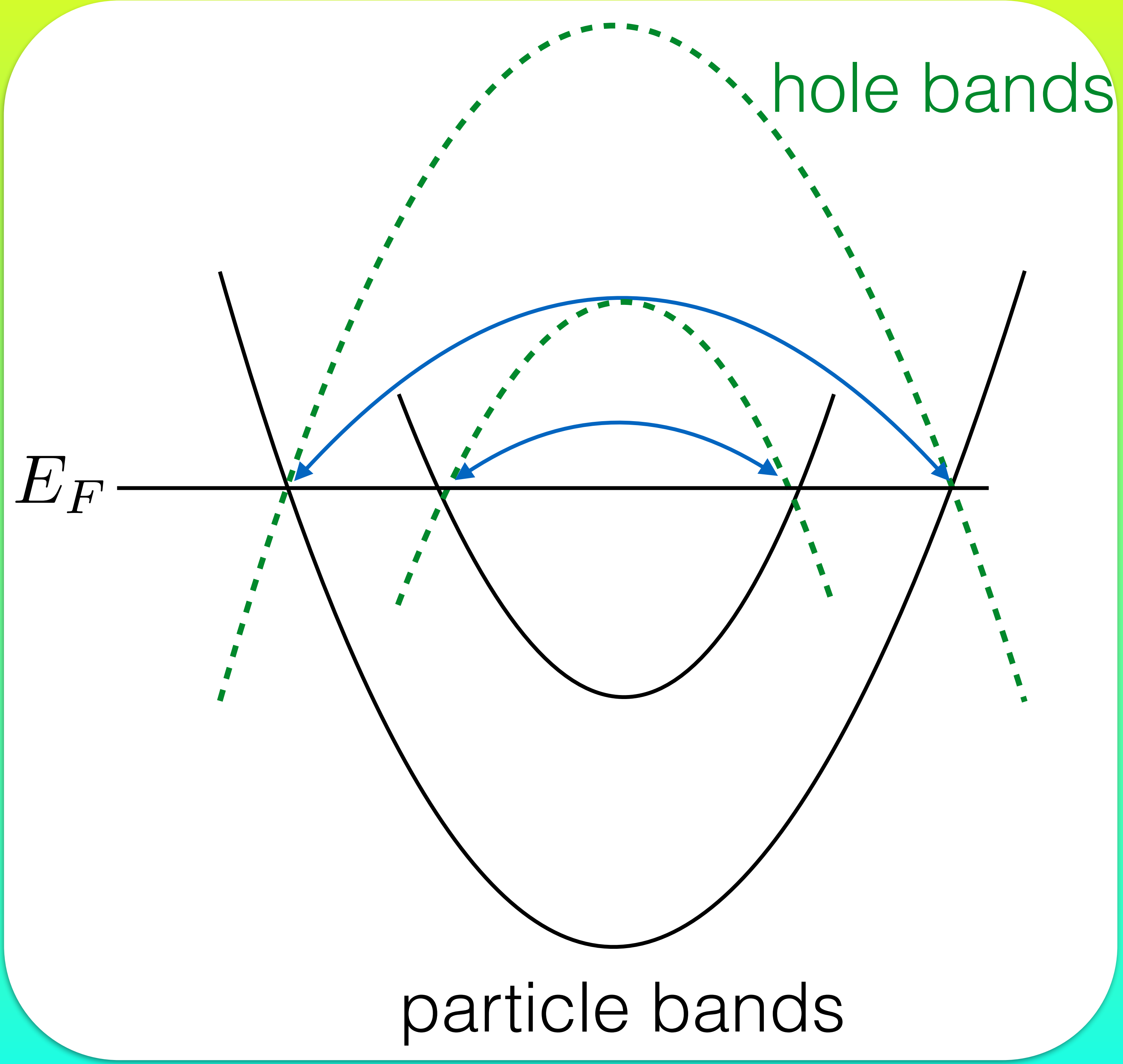

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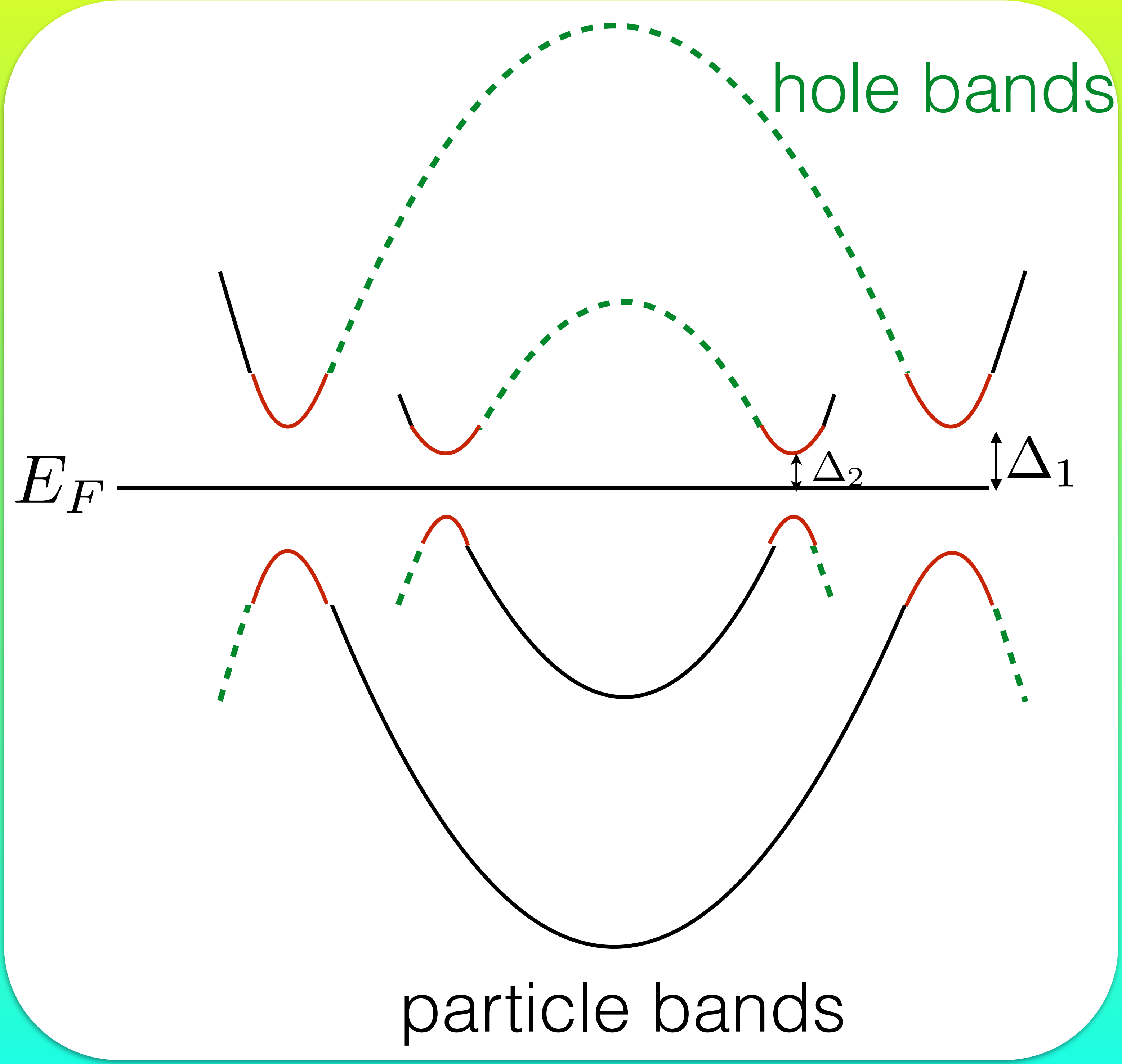

Multiband superconductivity

- Intrinsically interesting extension of superconductivity
- Allows for the interplay between the two gaps, novel dynamics
- Increasing number of materials are found to be multiband superconductors

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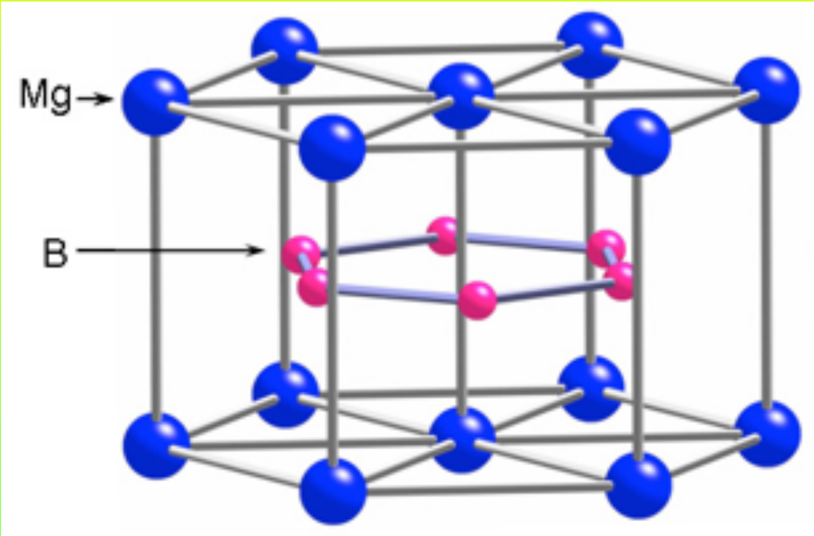
Our interest: is the specific material SrTiO3 (STO) and the interface between LaAlO3 (LAO) and STO a multiband superconductor?

Examples of Multiband SCs

- MgB2 (2001)



Nagamatsu, J. et al., 2001

- Fe based superconductors (2008)

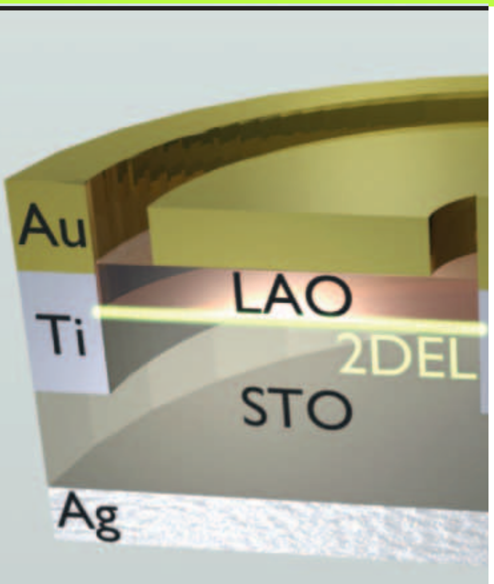
- various heavy fermion SCs ($PrOs_4Sb_{12}$ (2005), $CePt_3Si$,

  Seyfarth, PRL 2005 Mukuda, JPSJ 2009

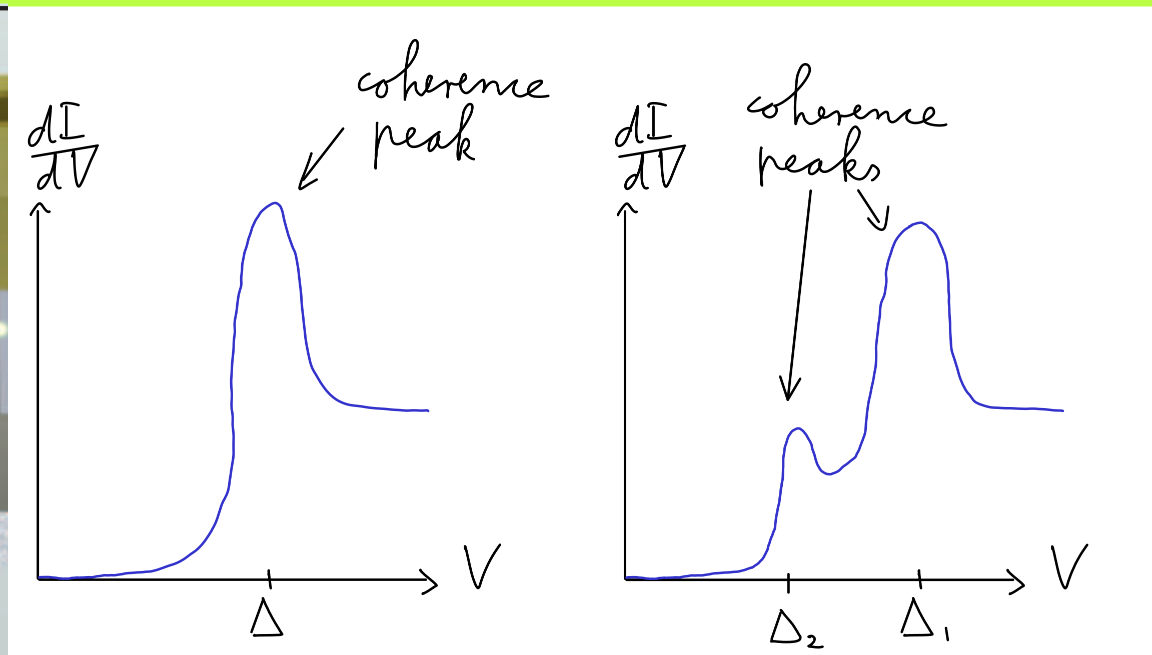
  uranium compounds…)

Detecting Multiband SC

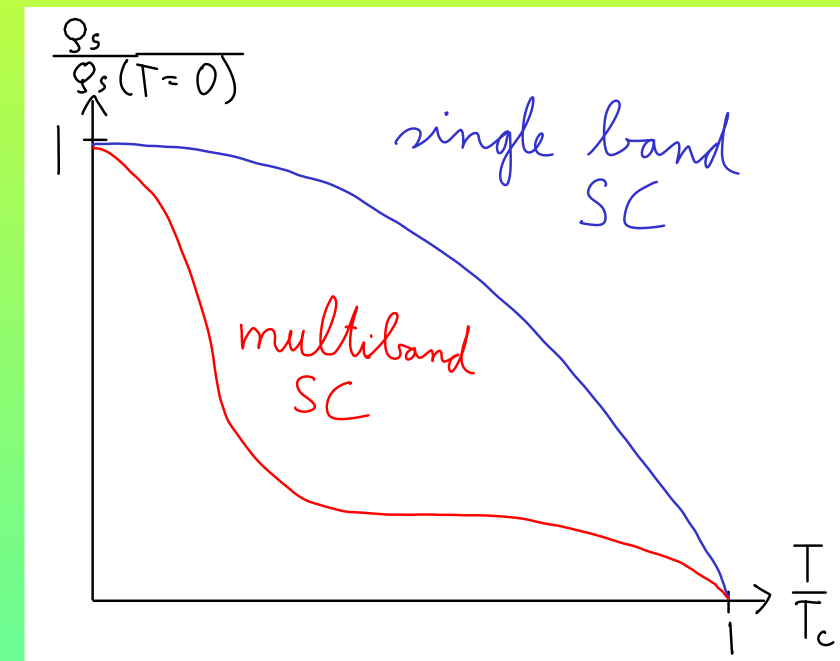
- Tunnelling spectroscopy: multiple coherence peaks



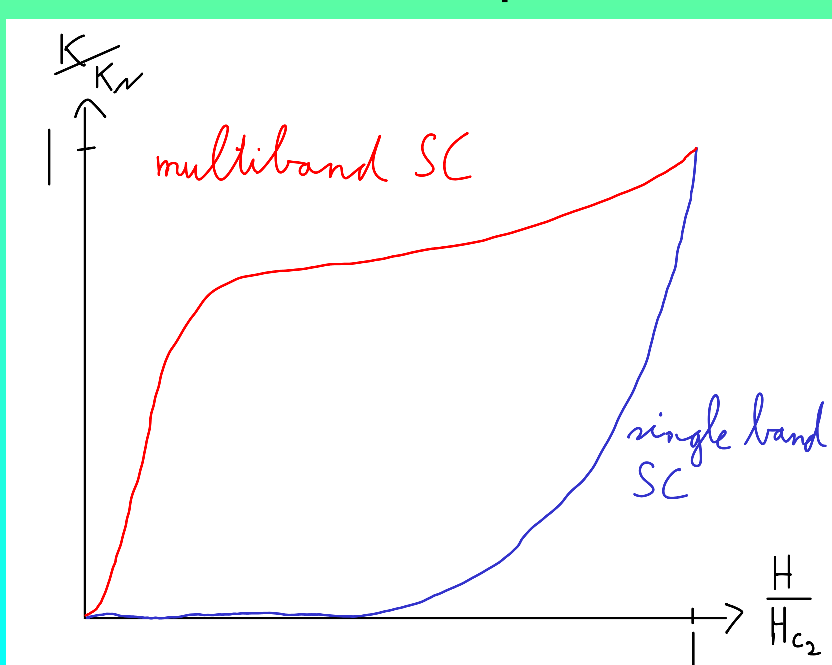
Richter, nature 2013



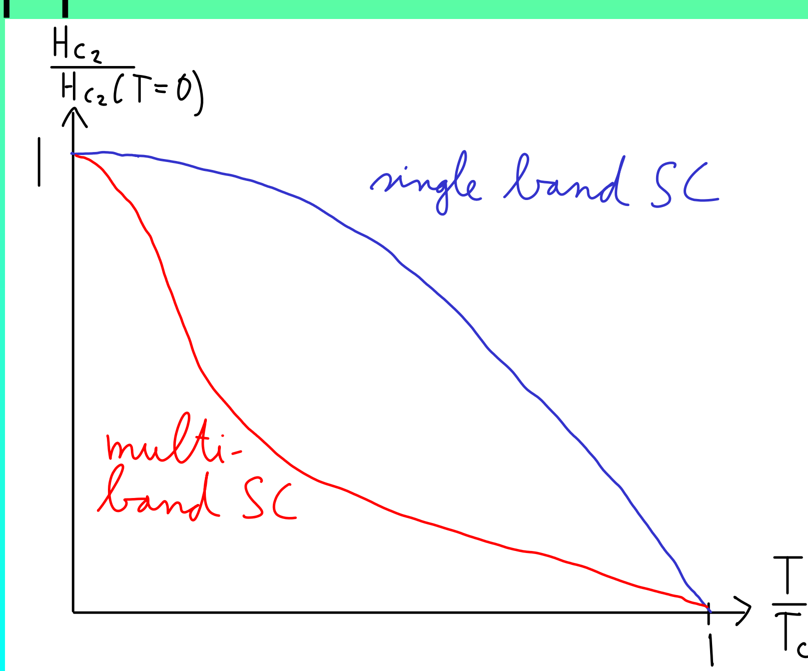
- superfluid density



- Heat transport

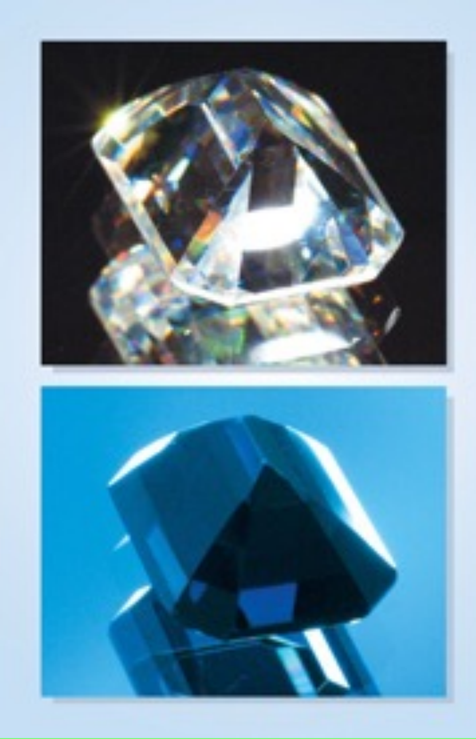


- upper critical field

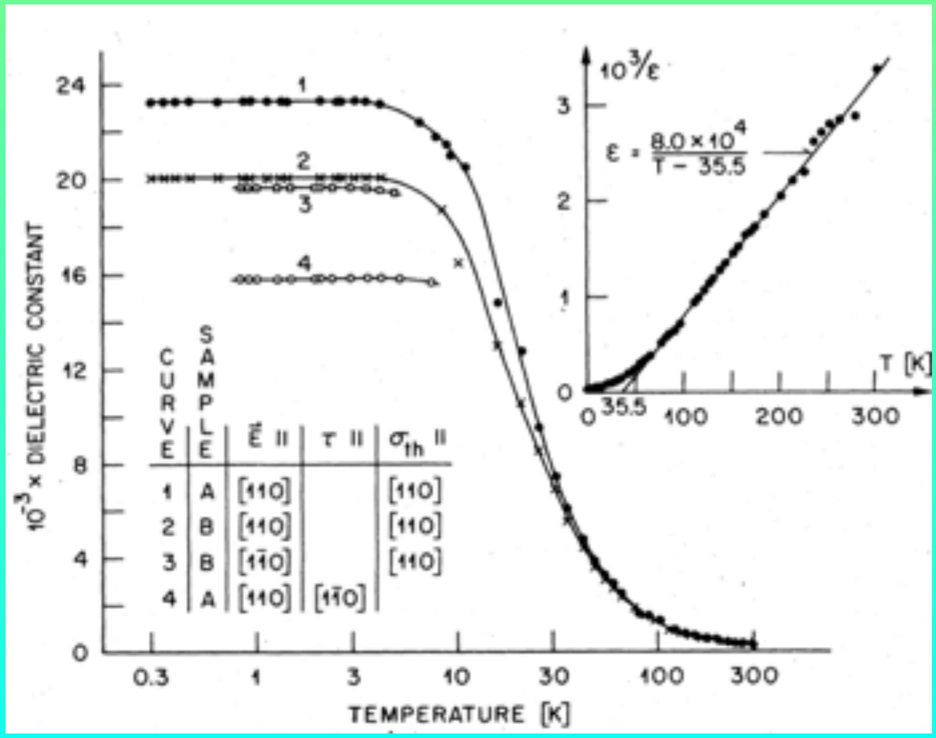


Strontium Titanate (STO)

- Wide bandgap insulator, bandgap ~3eV
- Doping with Nb, La or oxygen vacancies make it conducting
- Ferroelectric instability - nearly developed
- Has been studied experimentally and theoretically for 50 years



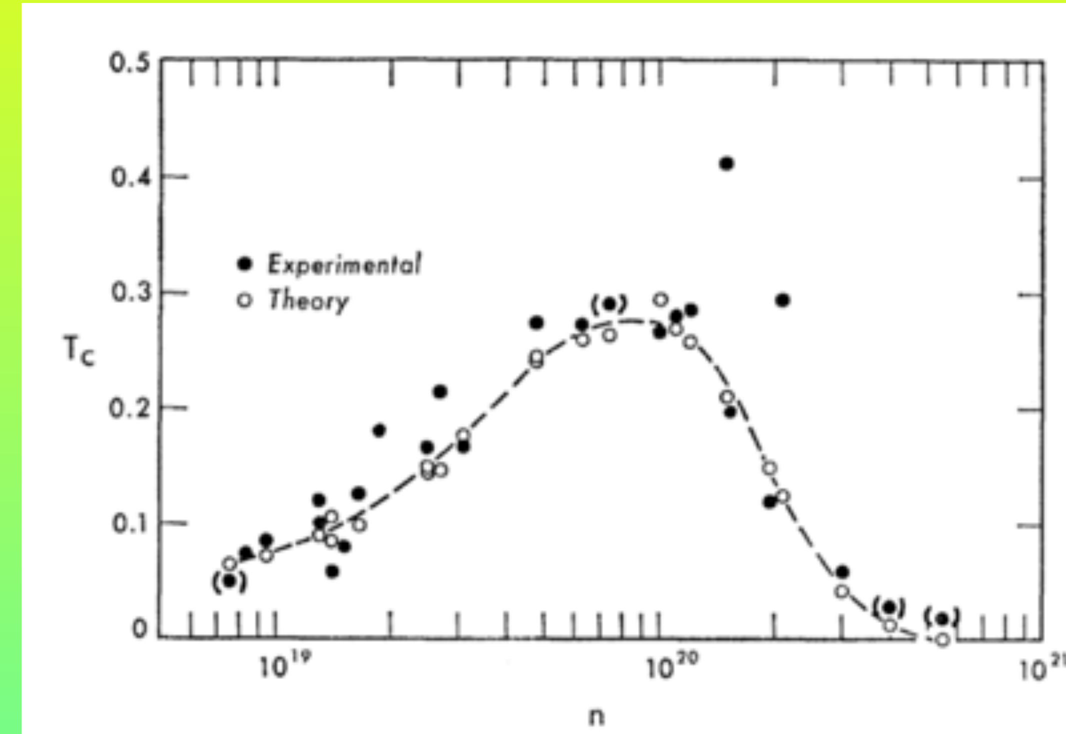
Mannhart, Nature 2004



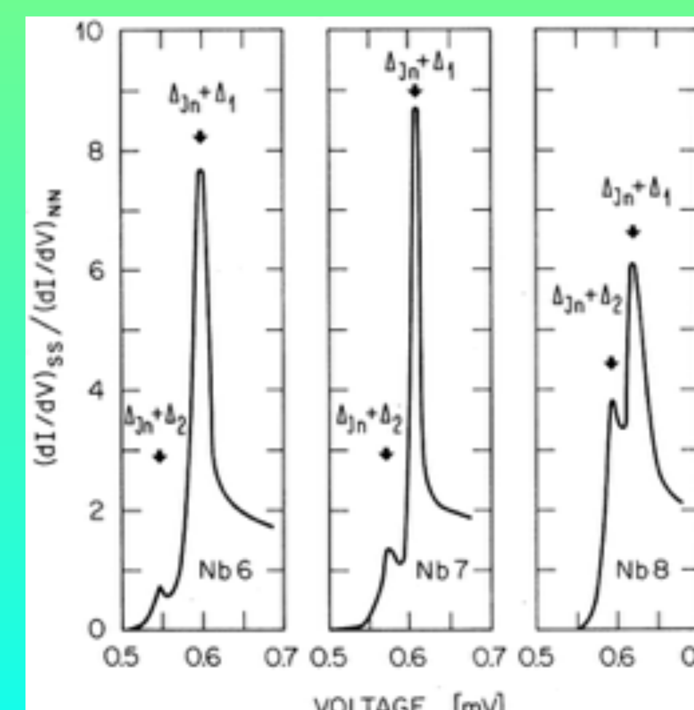
Müller, PRB (1979)

Superconductivity in STO

- First oxide superconductor to be discovered
- Doping-tunable SC dome
- Inspired the search which resulted in high Tc cuprate SC
- First material discovered to be a multiband supeconductor



Koonce et al PR 163 380



Binnig, PRL1980

v.d.Marel, PRB 2011

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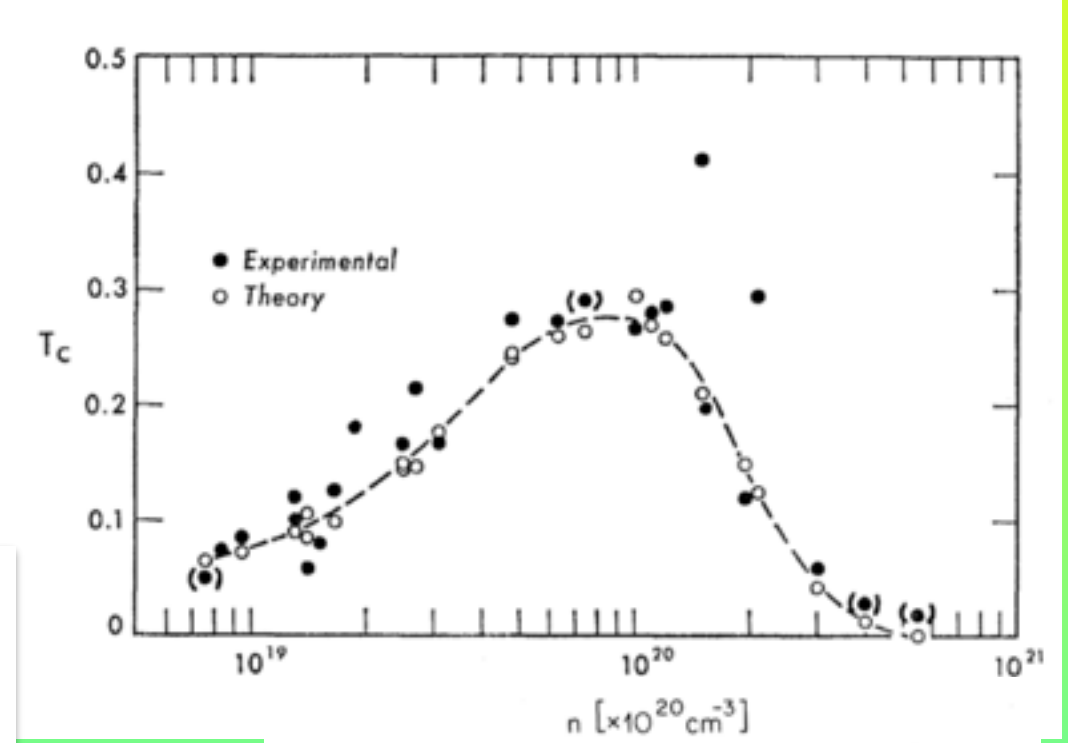
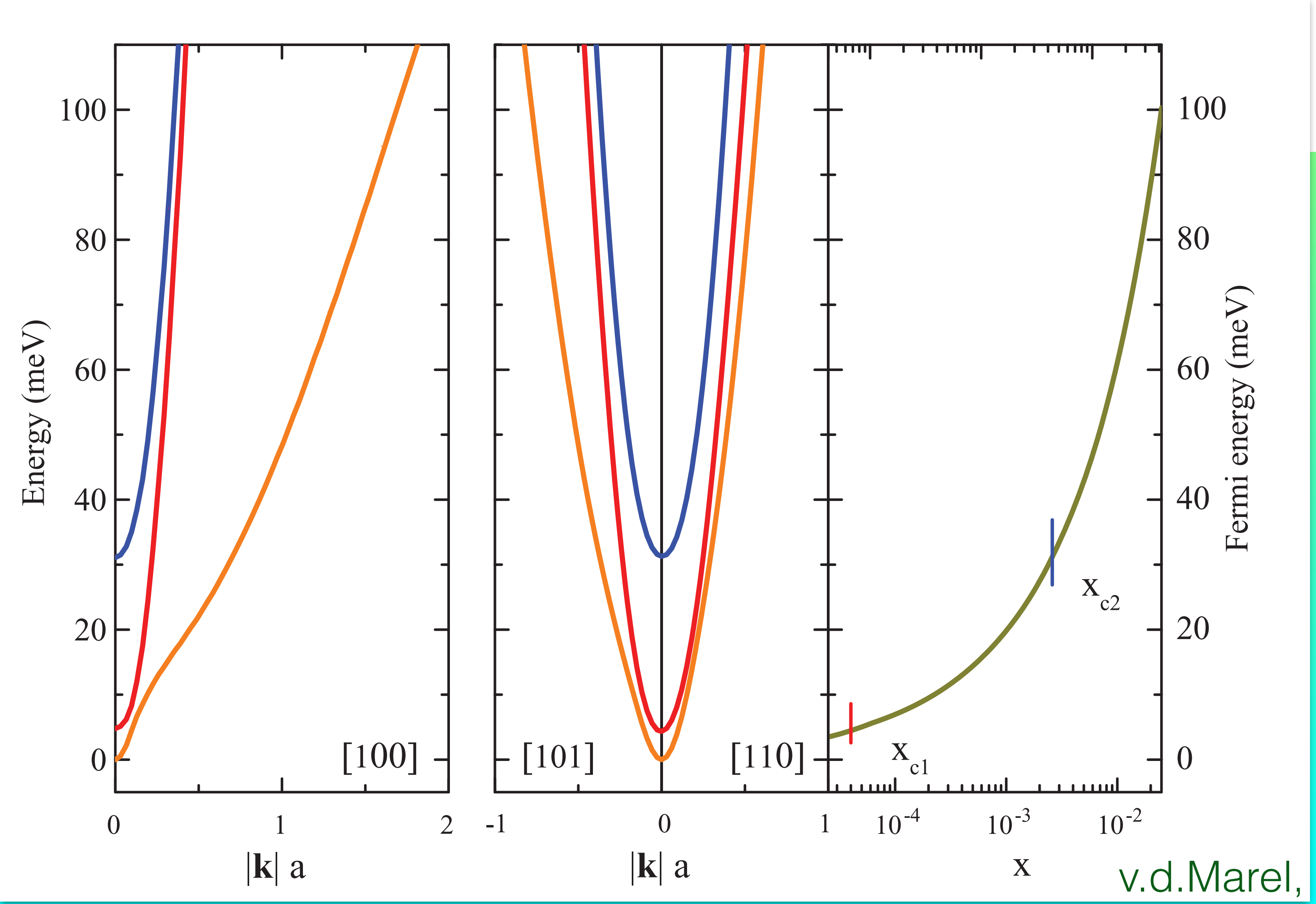
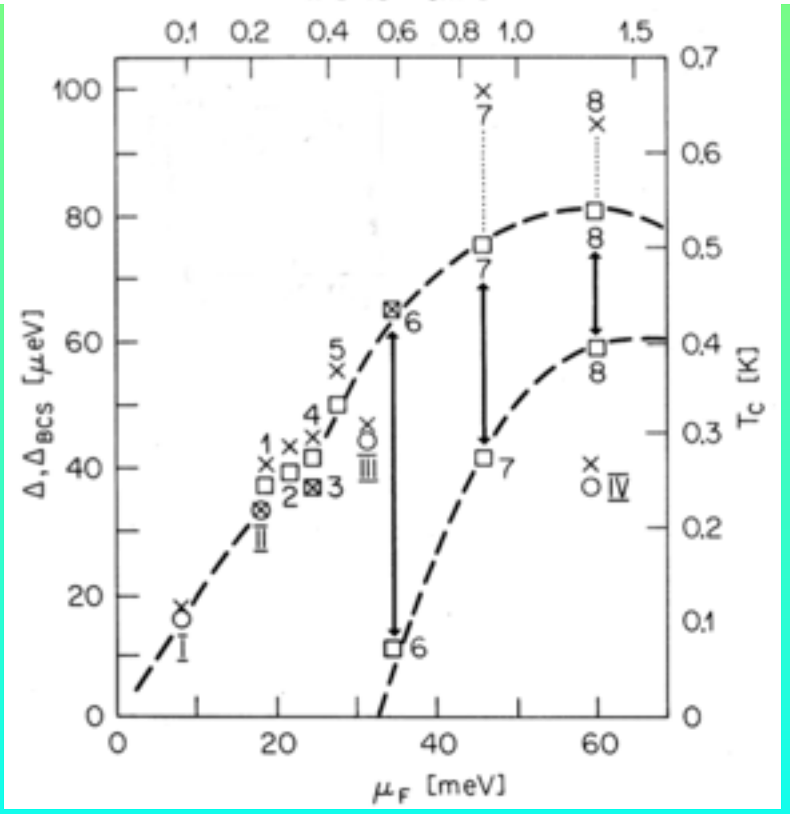




v.d.Marel, PRB 2011



Binnig, PRL1980

LAO/STO interface

- Like STO, LaAlO3 (LAO) is also an insulator (band gap ~ 5eV)
- But: when interface pure STO and LAO find a metallic interface layer

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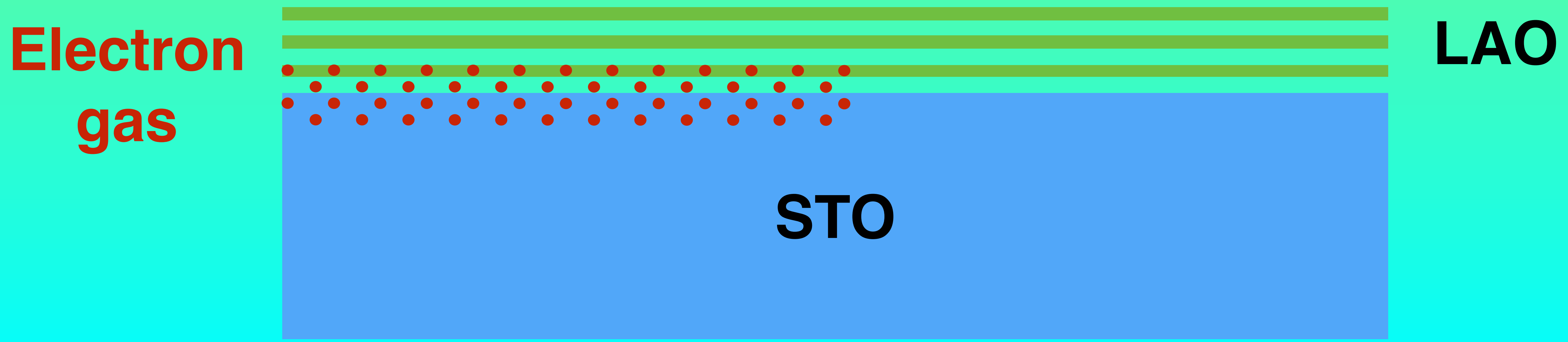

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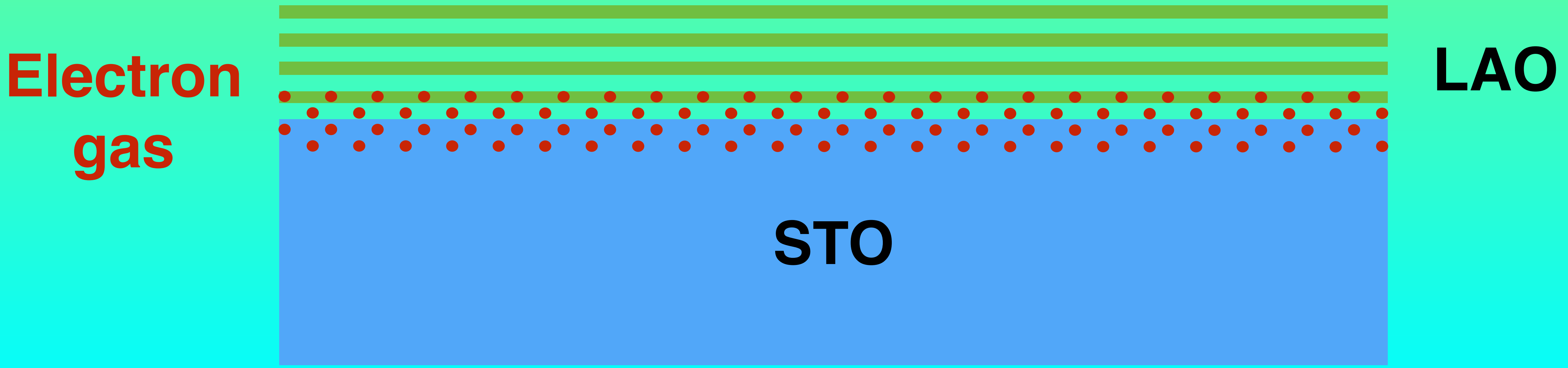

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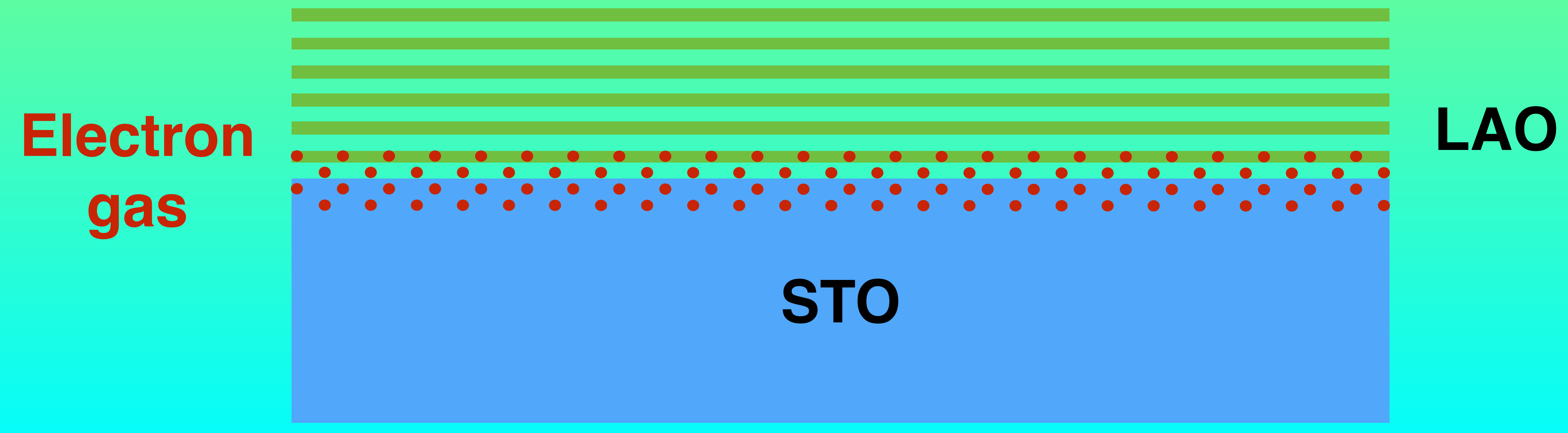
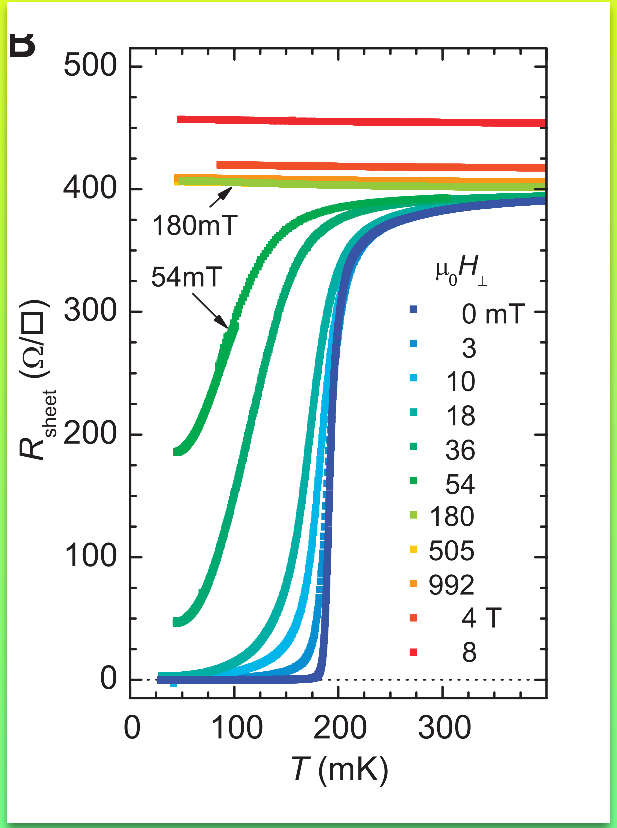
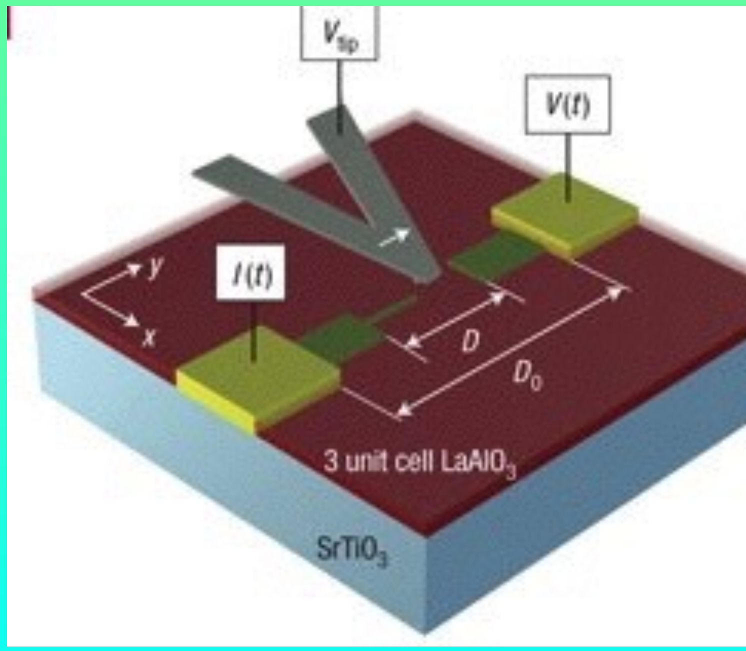


Superconductivity at the LAO/STO interface

- Metallic layer turns superconducting at low T
- For 3 layers of LAO, STM superconducting areas can be patterned with STM on nm scale
- Holds the promise for SC circuits and devices



Reyren, Science 2007

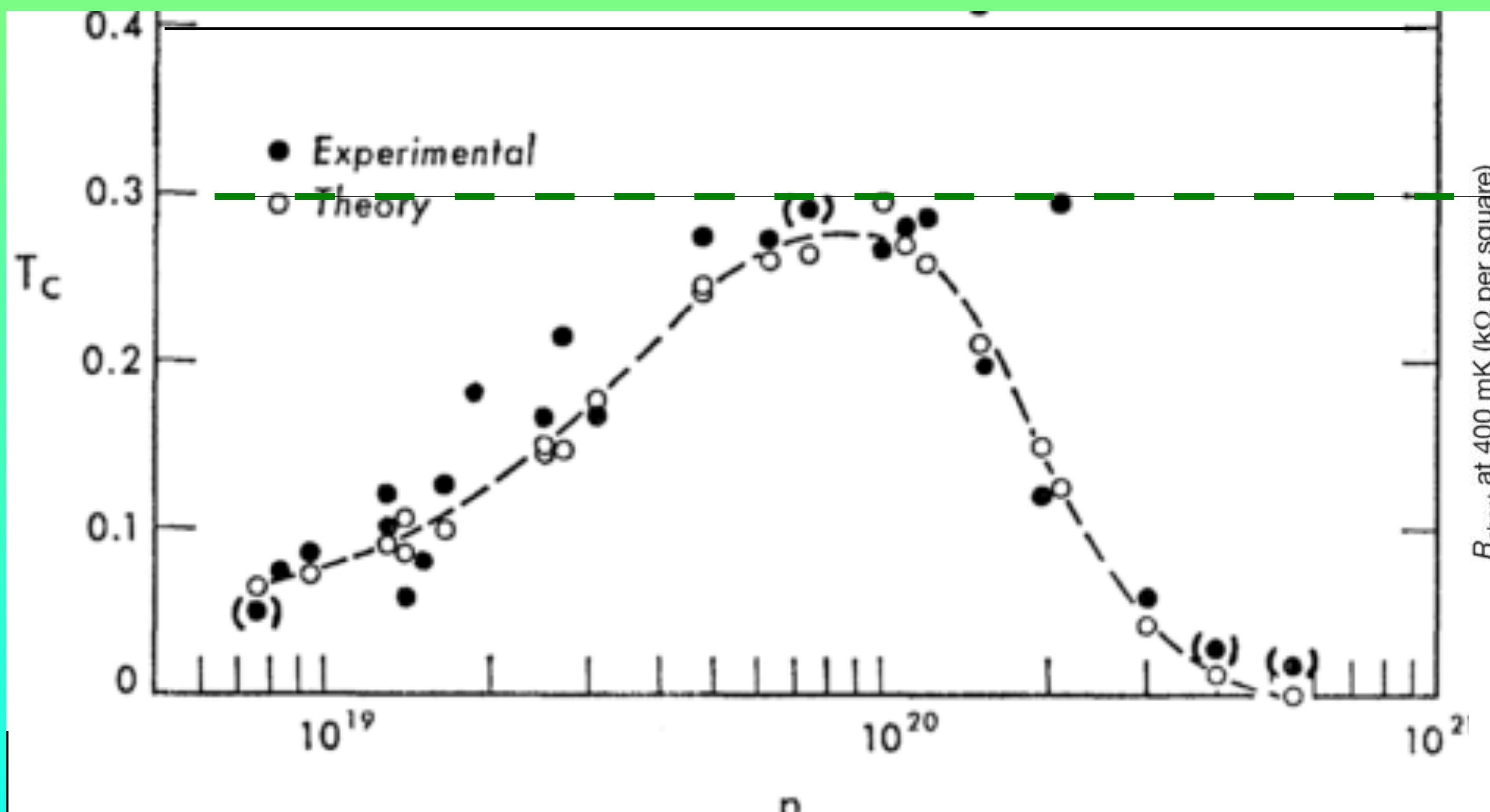


Cen, Nat. Mat. 2008

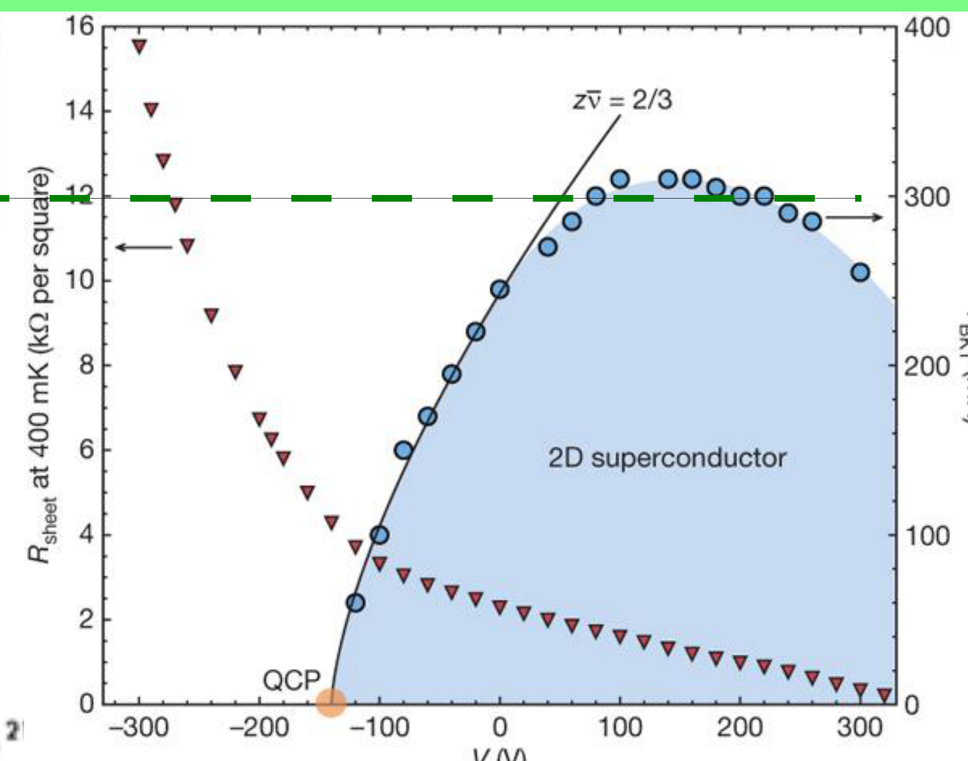
Central question: What is the relation between bulk and interface STO?

- Tc is similar (≅300mK), robust to quality variations of the sample/interface material

- As a function of doping/gate voltage a narrow superconducting dome appears.



Koonce PR 1967

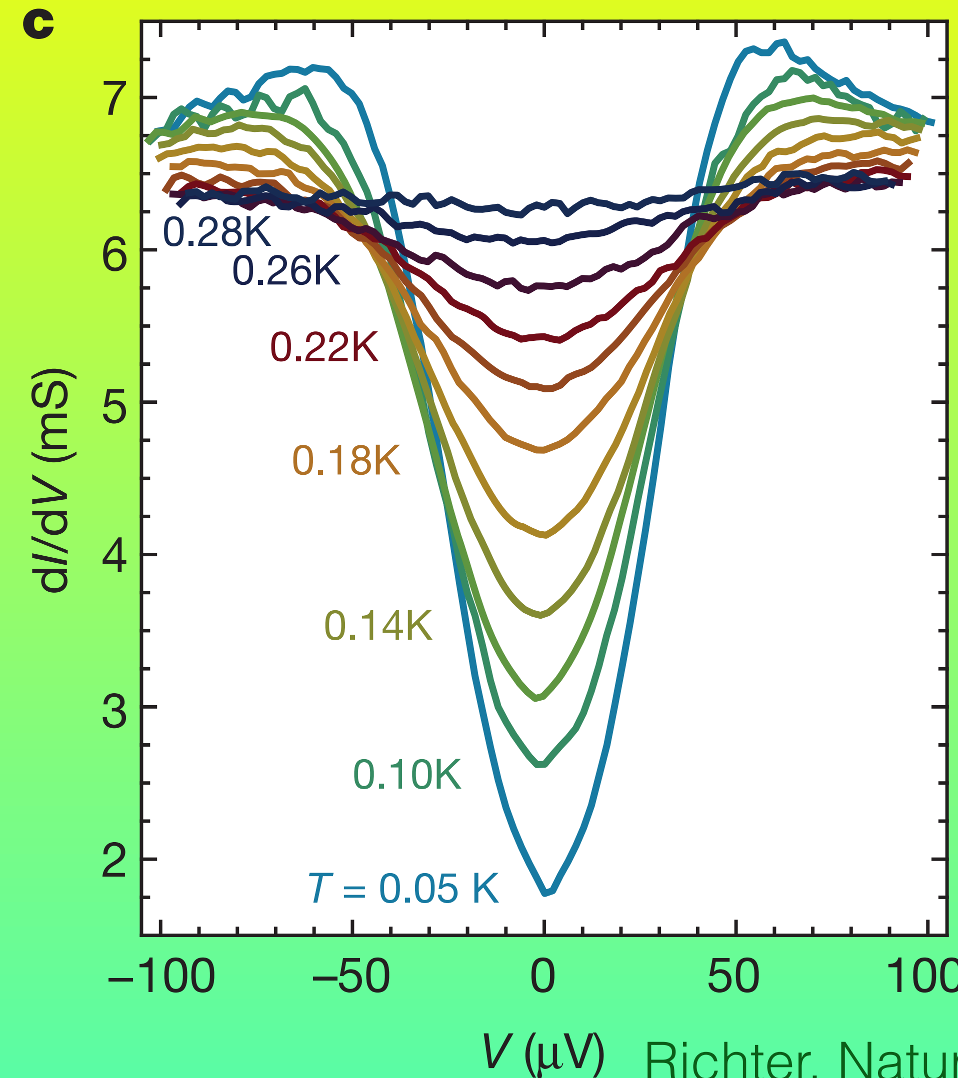


Caviglia Nature 2008

Is LAO/STO a multiband SC, like STO?

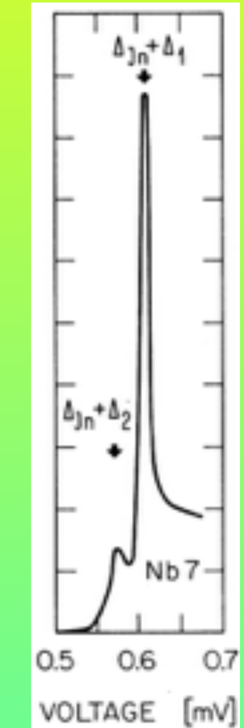
Probes which have tried to address this issue

- Tunnelling spectroscopy

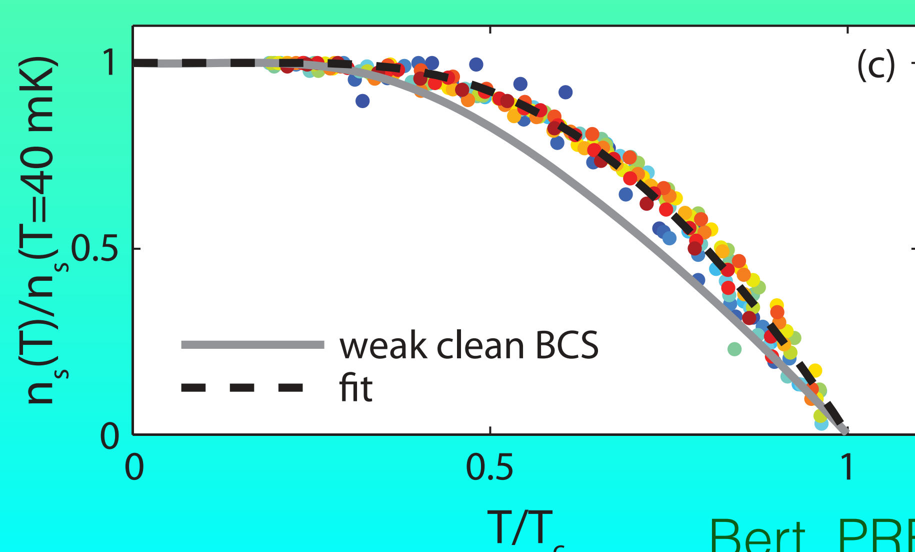


Richter, Nature 2013

compare STO

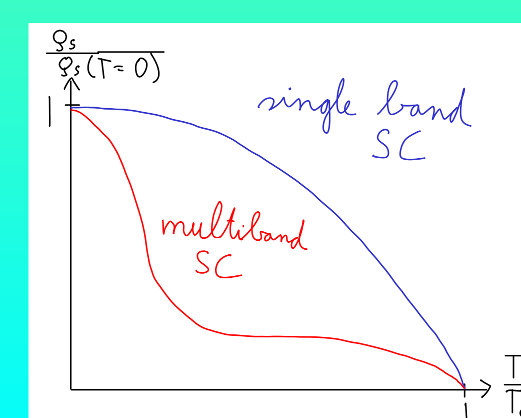


- Superfluid density



Bert, PRB 2012

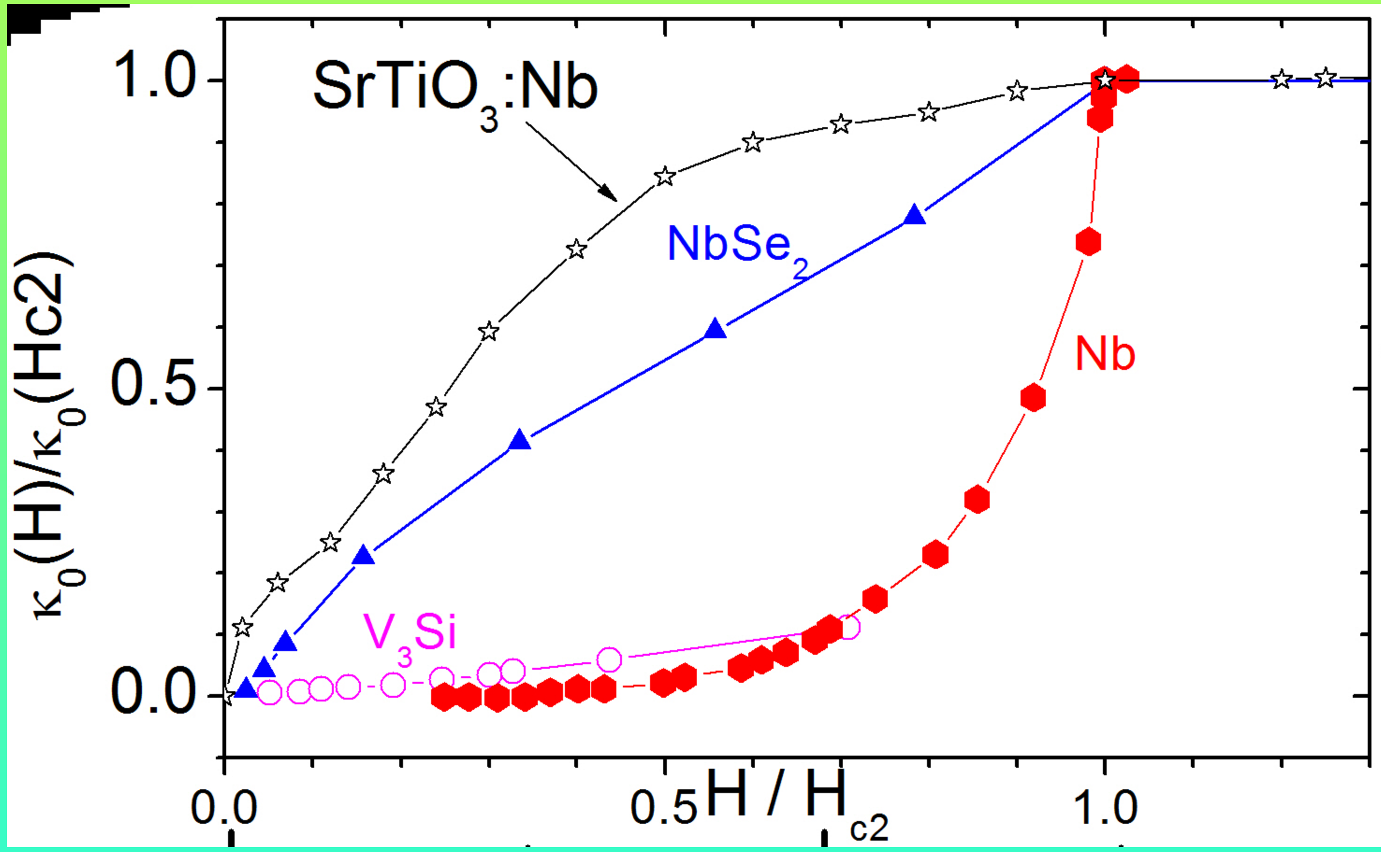
compare



Is LAO/STO a multiband SC, like STO?

Other potential probes

- Heat transport
- Heat capacity
- impractical for interface



Lin 1409.2423

Suggest looking at the upper critical field H_{c2} as a probe for multiband superconductivity in LAO/STO

H_{c2} as a probe for multiband SC in LAO/STO and STO

H_{c2} is one of the few probes applicable both to the bulk and interface system

- Calculate expected H_{c2} behaviour for both bulk and interface
- Show characteristic multiband behaviour
- Allows direct comparison of bulk and interface system

Disordered bulk STO: quasiclassical Usadel equations

- Solve linearised Usadel equations with a B-field $H \parallel \hat{\vec{z}}$.

$$2\omega f_m - D_m \left(\nabla_x^2 + \nabla_y^2 + \nabla_z^2 + \frac{4\pi i H x}{\phi_0} \nabla_y - \frac{4\pi^2 H^2 x^2}{\phi_0^2} \right) f_m = 2\Delta_m$$

m: band index ($\in \{1, 2\}$),
D_m: Diffusion coefficient in the band
f_m: quasiclassical anomalous Green's function

- Linearised: valid for infinitesimal gaps Δ, so at T_c.

- 2-band gap equation:

$$\Delta_m = 2\pi T \sum_{\omega > 0}^{w_D} \sum_{m'} \lambda_{mm'} f_{m'}(\vec{r}, \omega)$$

λ: coupling constants

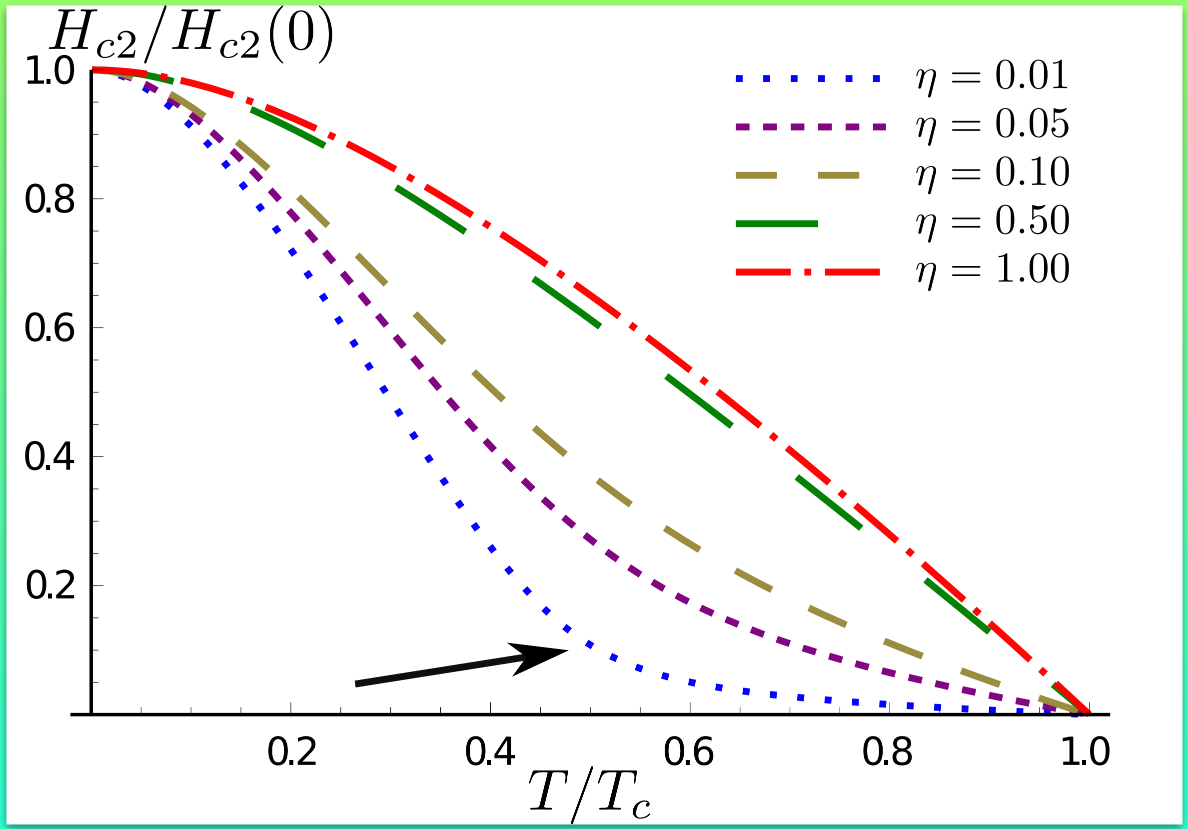
- Solving this equation gives pairs (H, T) and since $T = T_c$ (linearised equations) we get pairs (H_{c2}, T_c).

Results for H_{c2}

JME & Balatsky, arXiv:1401.5318

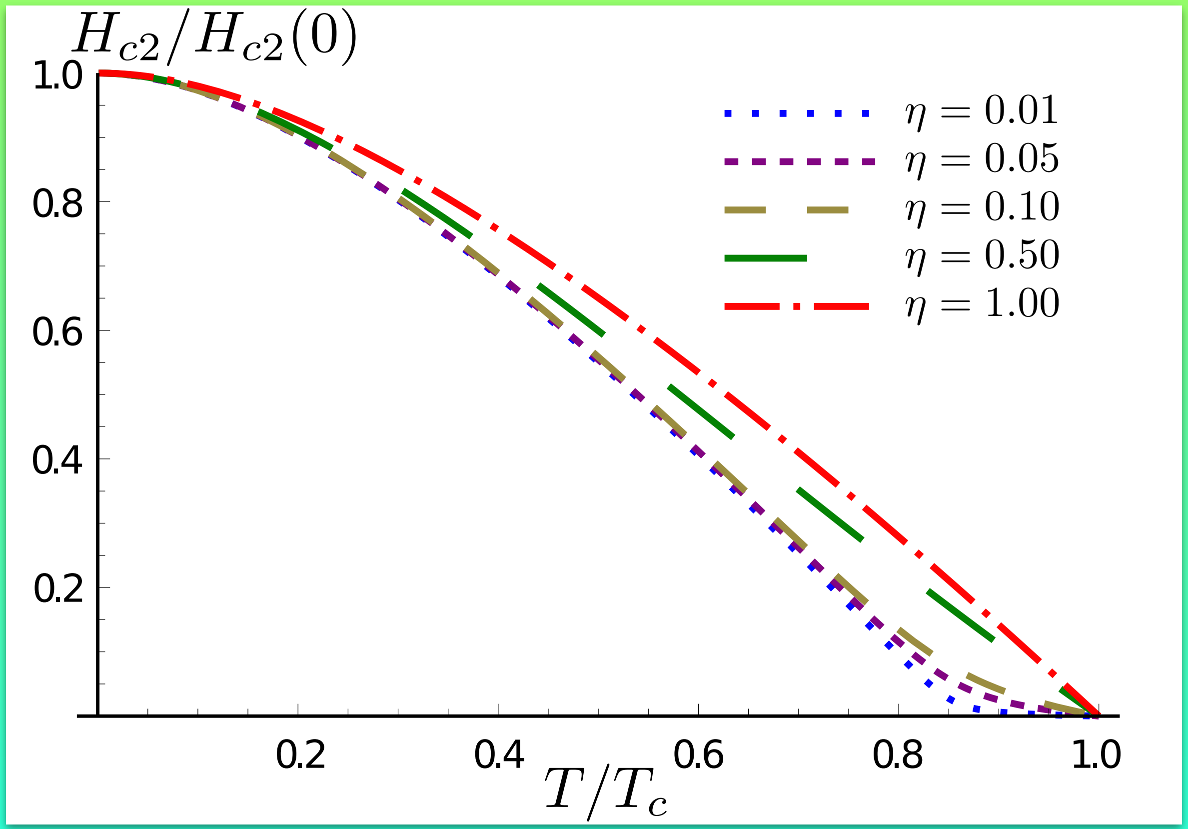
Solve for two sets of parameters:

$$\eta = D_2/D_1$$



Parameters: Fernandes, PRB 2013

$$\lambda_{11} = 0.14, \lambda_{22} = 0.13, \lambda_{12} = 0.02$$

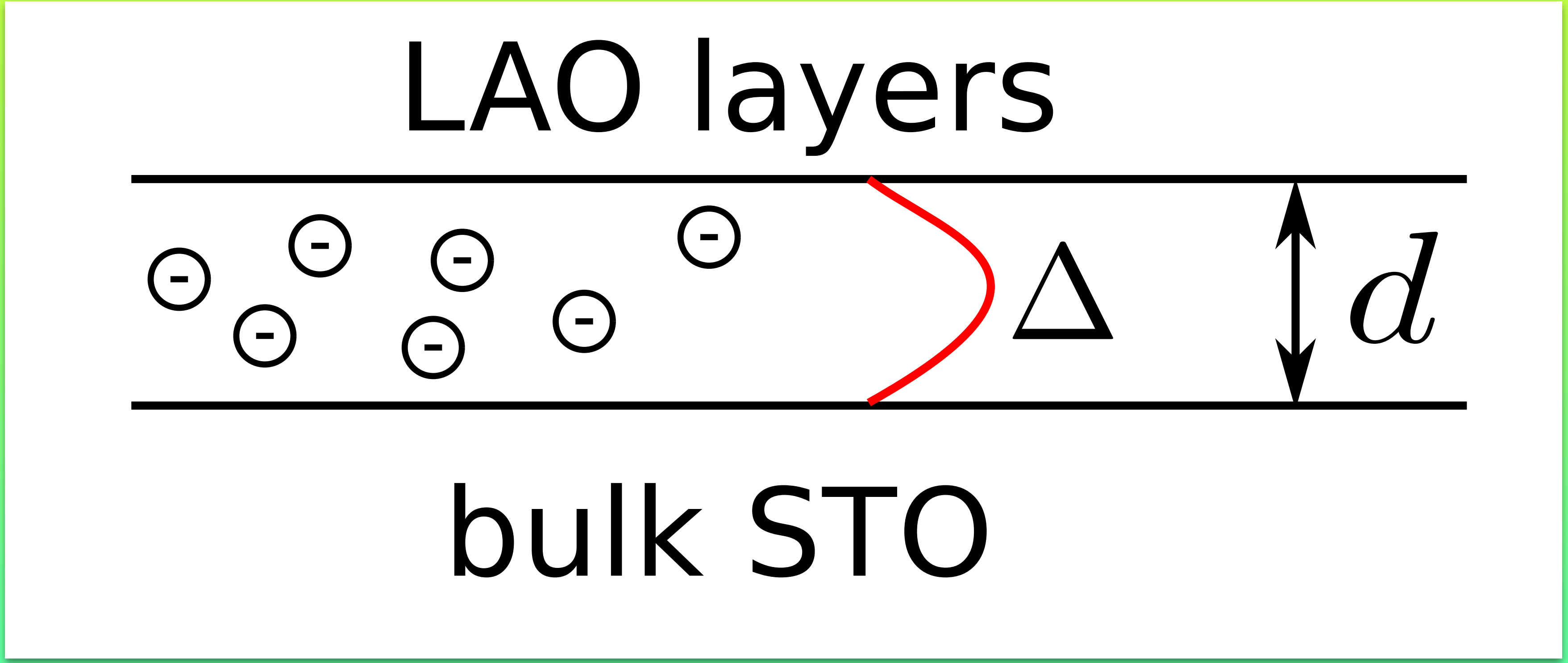


Parameters: Bussmann-Holder, Ferroelectrics 2010

$$\lambda_{11} = 0.3, \lambda_{22} = 0.1, \lambda_{12} = 0.015$$

Interface system

Thin superconducting layer



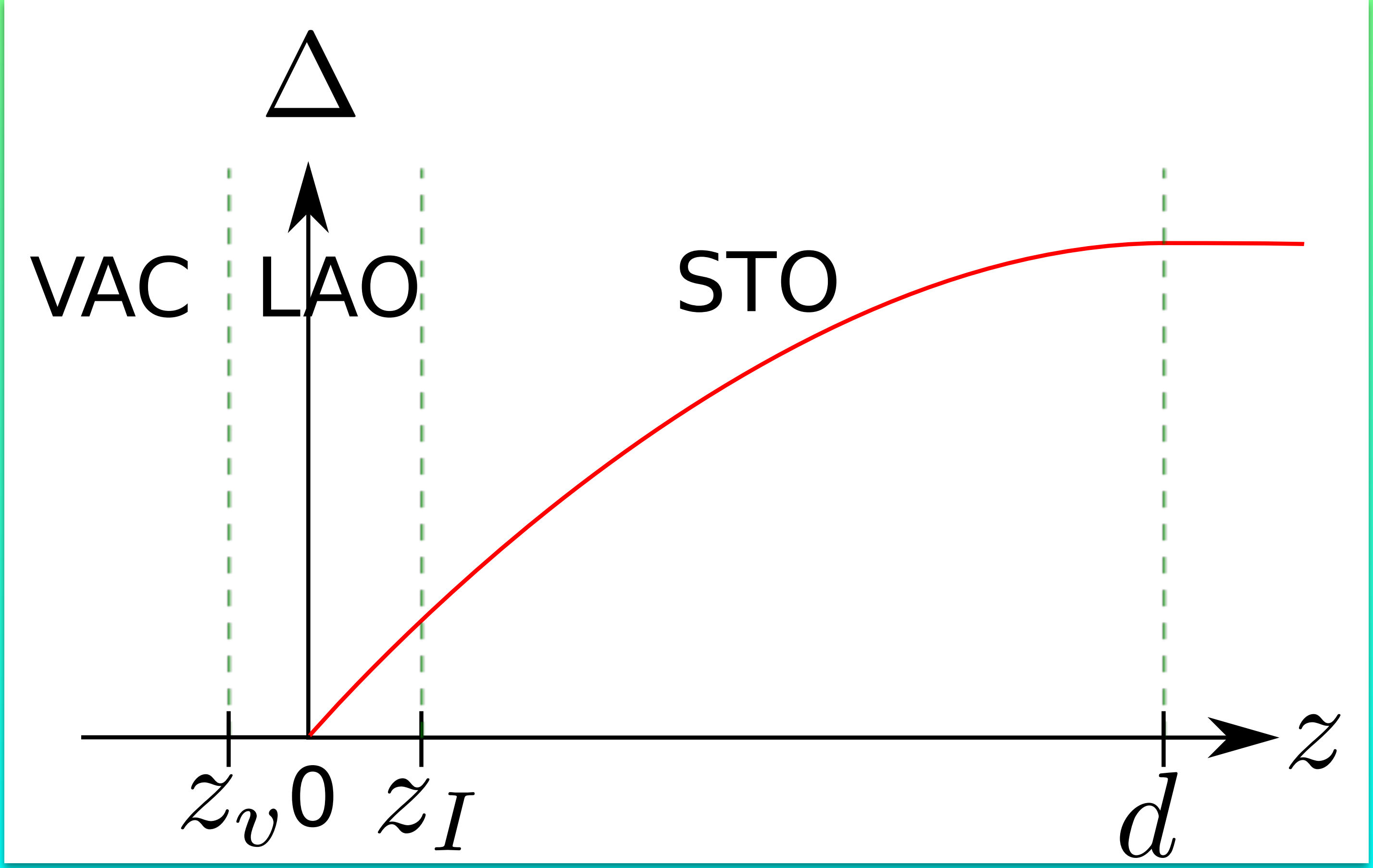
- retain ∇_z term in the Usadel equation
- Incorporate the effects of Rashba spin-orbit coupling

Finite thickness

- need to retain ∇_z term in

$$2\omega f_m - D_m\left(\nabla_x^2 + \nabla_z^2 - \frac{4\pi^2 H^2 x^2}{\phi_0^2}\right) f_m = 2\Delta_m$$

- At the boundary to the vacuum, Δ =0
- An an interface between a SC and a metal $\frac{\mathrm{d}\Delta}{\mathrm{d}z} = 0$
- thickness: d~12 nm
- $\nabla_z^2 \rightarrow -\frac{\pi^2}{4d^2}$
- Incur an extra energy cost: effectively H increases



Spin-orbit coupling (SOC) at the interface

- Due to inversion symmetry breaking get strong Rashba SOC

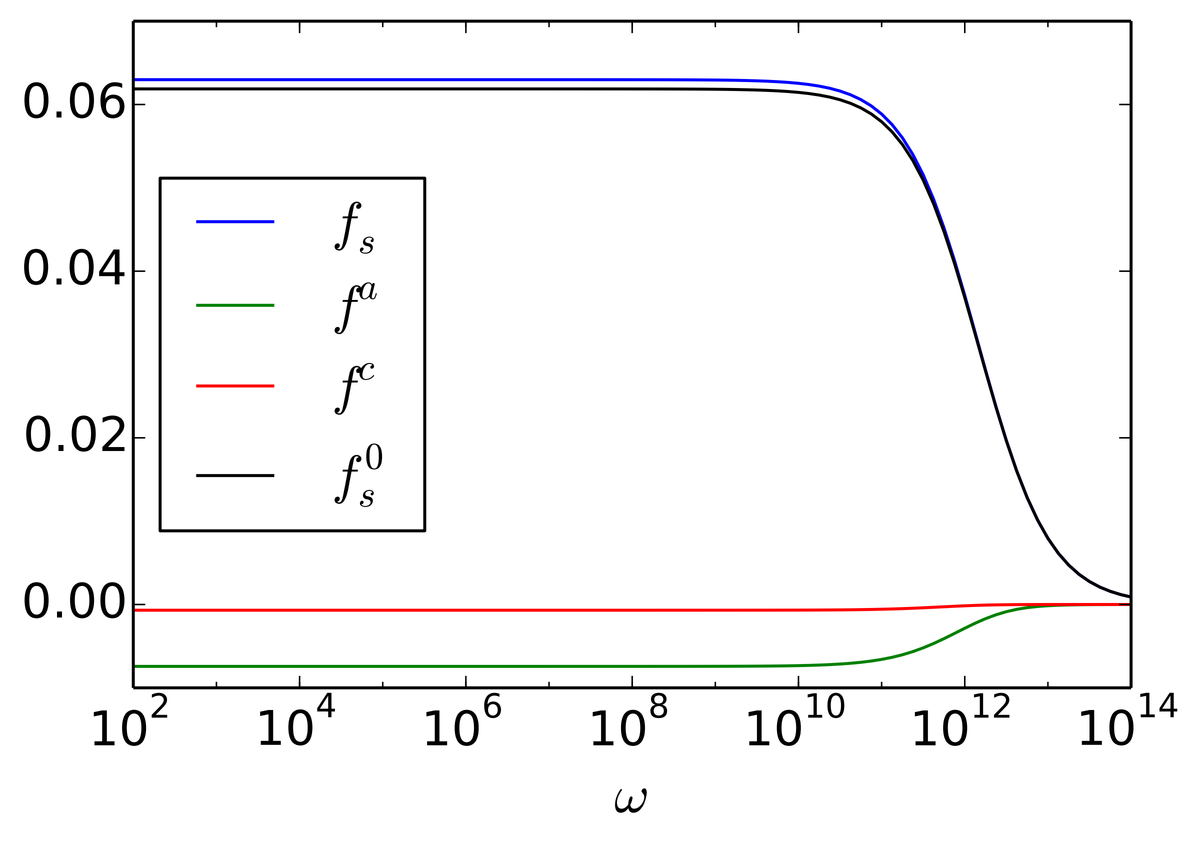
- Leads to a modification of the momentum operator, anomalous Green's function *f* becomes a matrix

$$\nabla_x f \to \nabla_x f + \frac{i\alpha m_e}{\hbar}[\sigma_y, f] \quad \alpha : \text{SOC coupling strength}$$

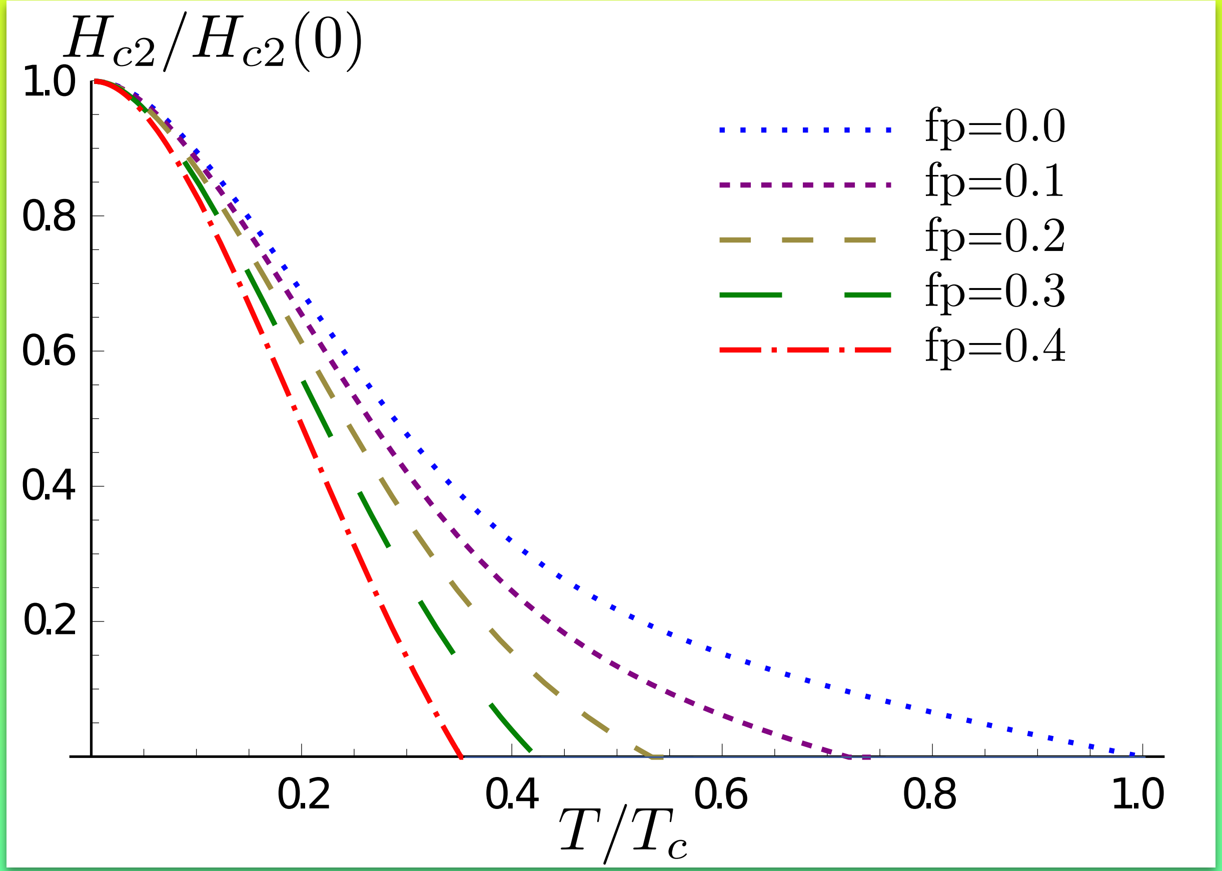
- singlet and triplet components of *f* get coupled

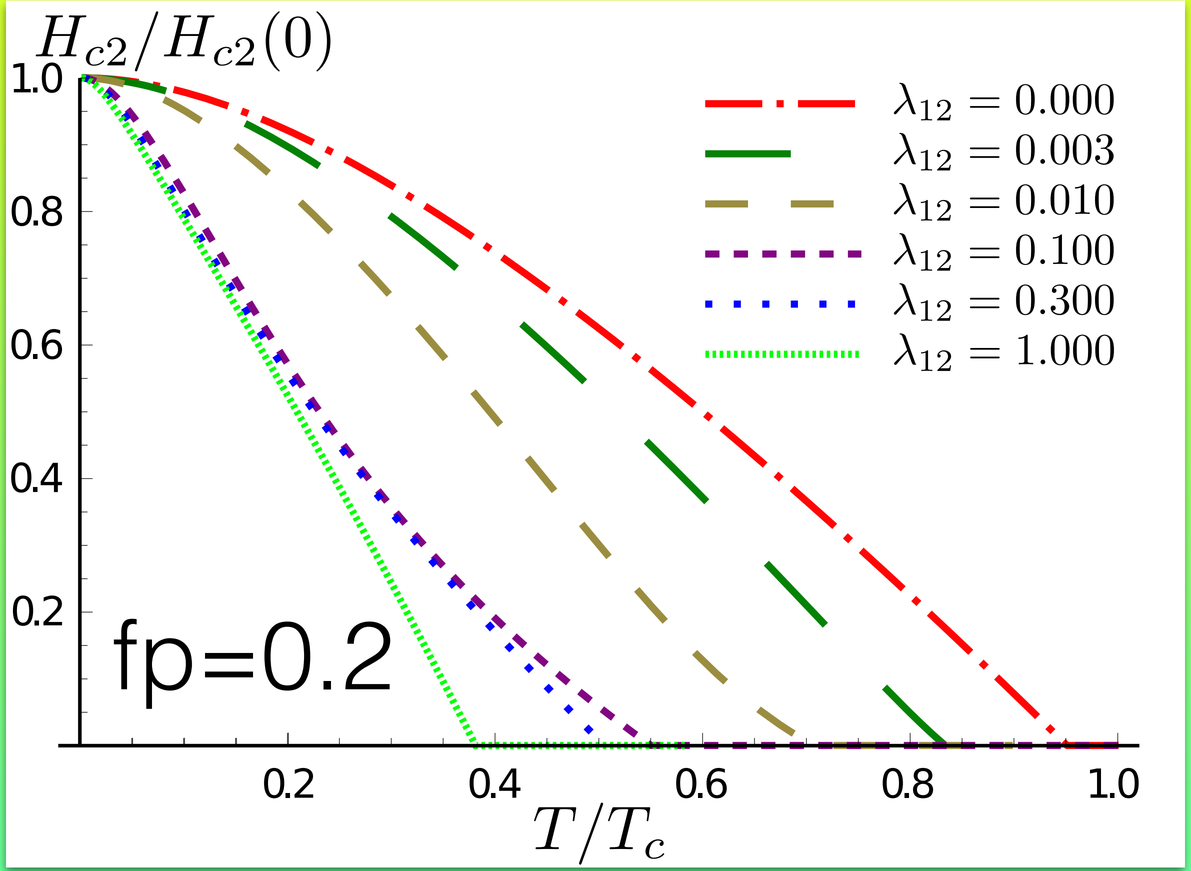
- Concentrate on dominant singlet component

- singlet f gets energy penalty



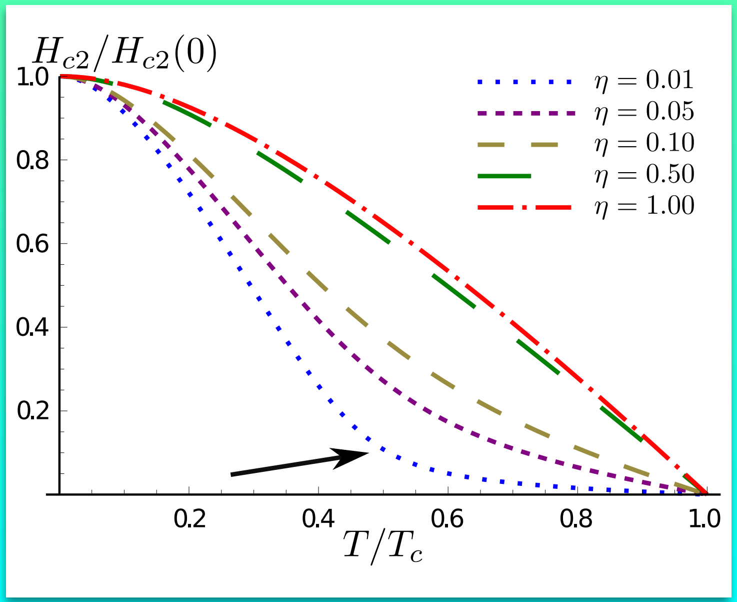
LAO/STO results





$$\lambda_{11} = 0.14, \lambda_{22} = 0.13, \lambda_{12} = 0.02$$

Comparison: bulk STO results

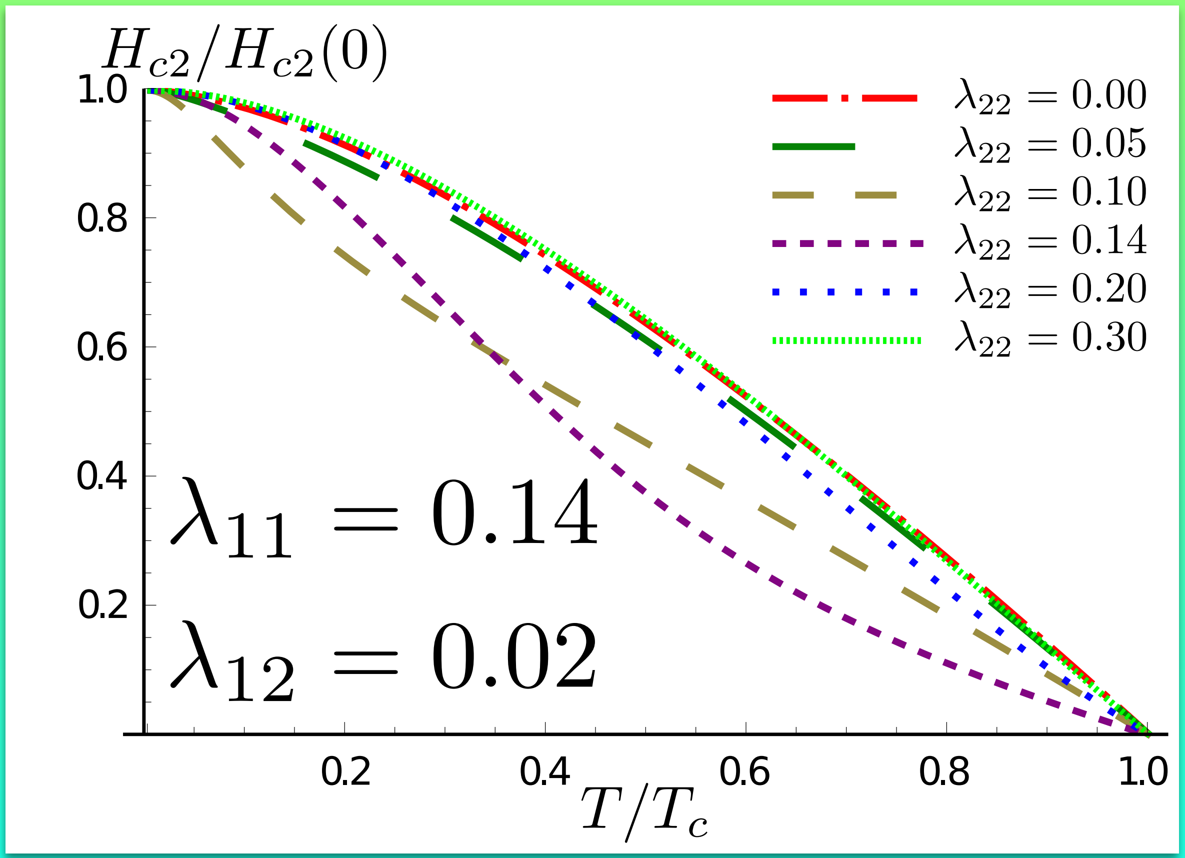


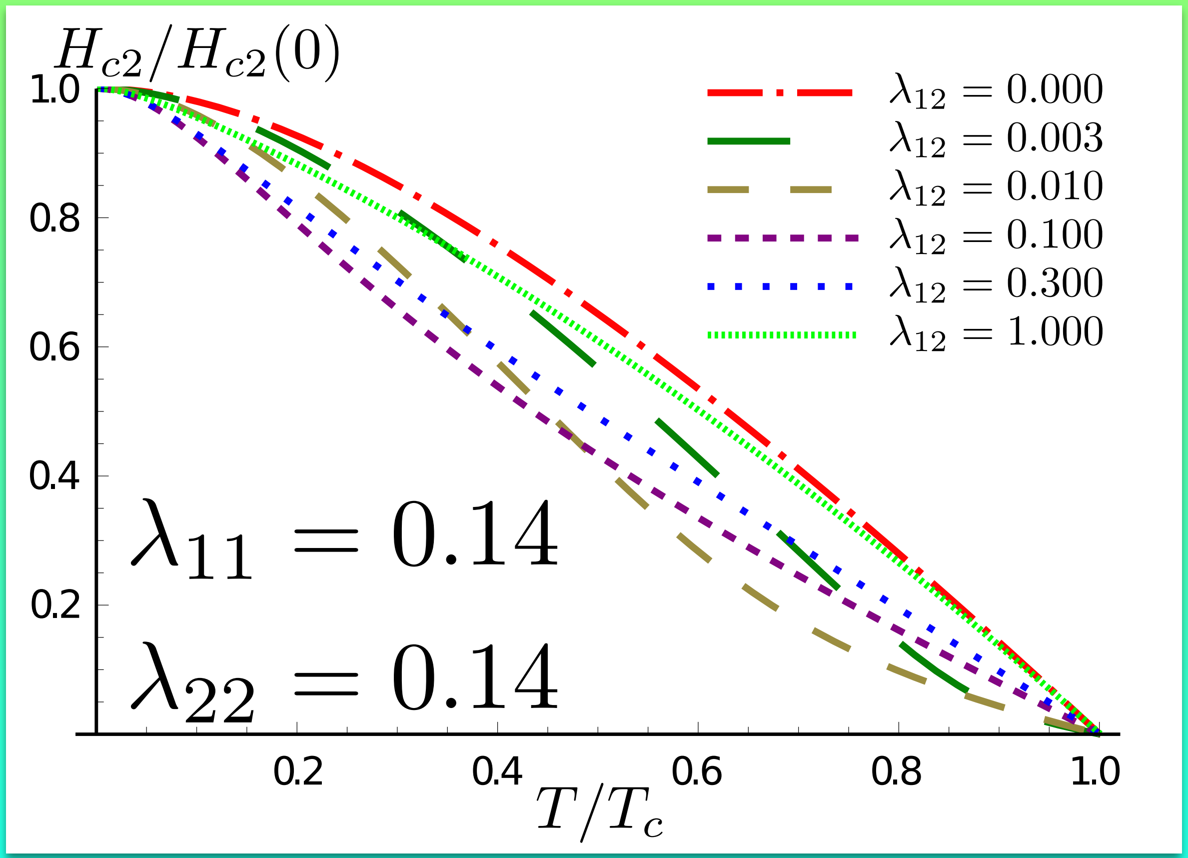
Conditions under which H_{c2} is a useful probe

Hc2 is useful when

- $\lambda_{11} \approx \lambda_{22}$

  $\lambda_{12} \ll \lambda_{11}$

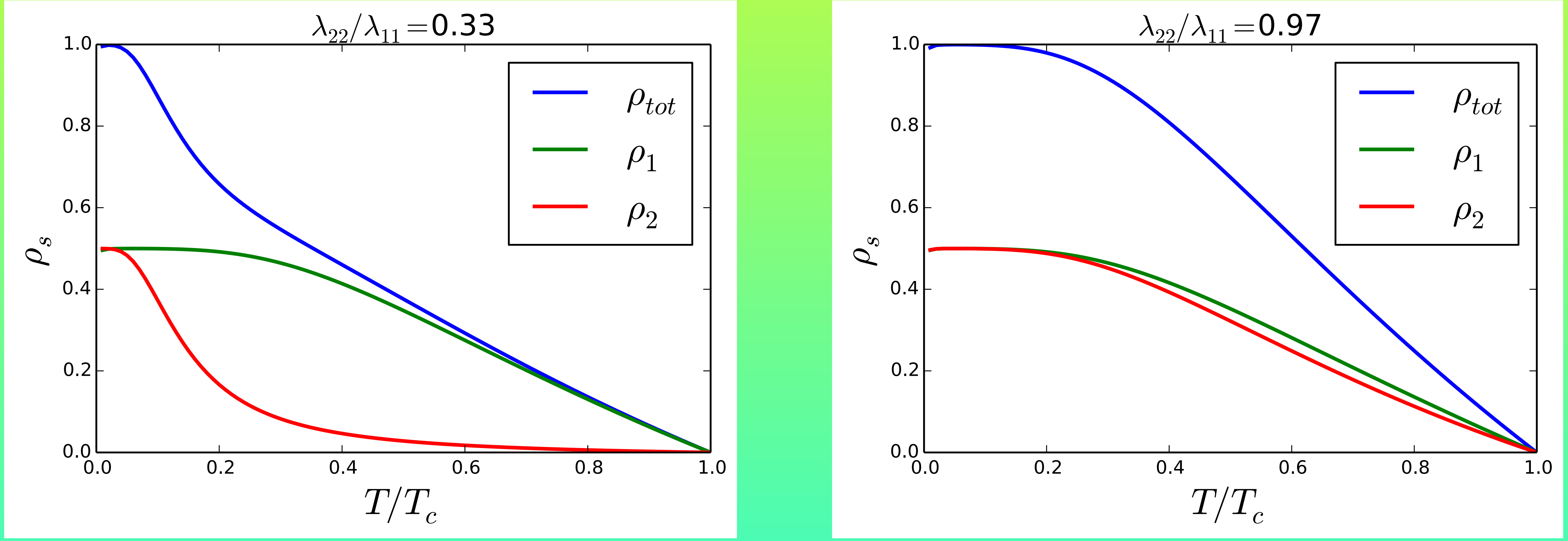




$$\eta = \frac{D_2}{D_1} = 0.1$$

Hc2 and superfluid density are complementary probes

- Superfluid density useful when: $\lambda_{11} \gg \lambda_{22}$

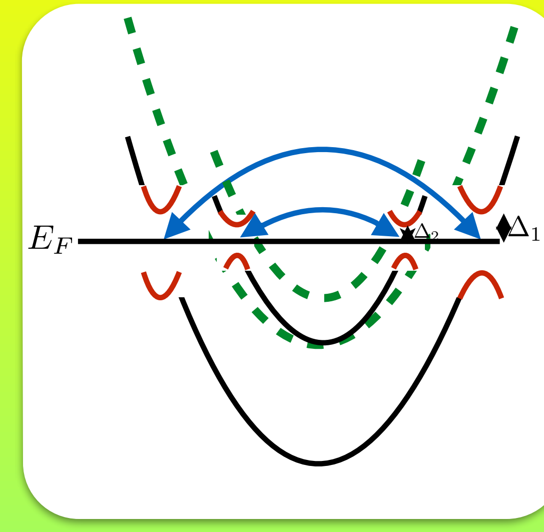


following Kogan, PRB 2009

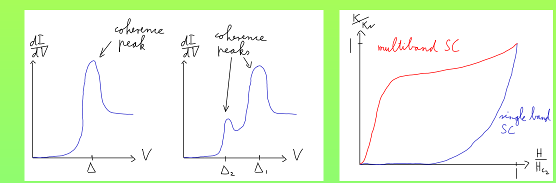
- Upper critical field Hc2 useful when: $\lambda_{11} \approx \lambda_{22}$
  measure onset of SC

Summary

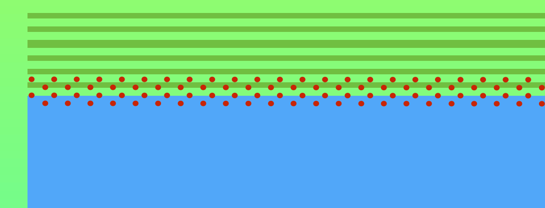
- Multiband superconductivity: Two or more gaps open



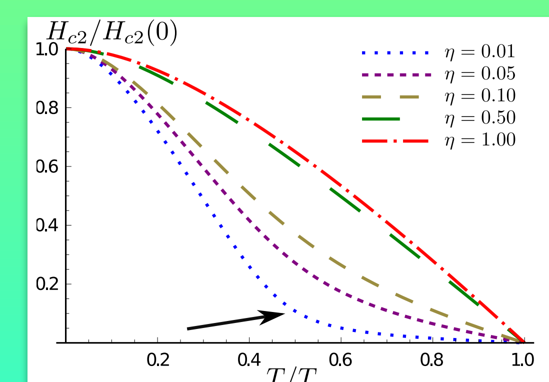
- Various techniques for detecting MBSC



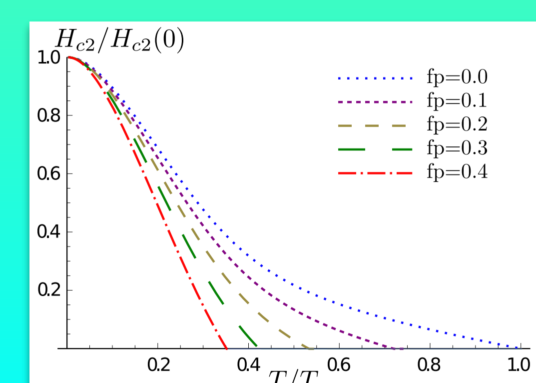
- LAO/STO interface: metallic layer



- Upper critical field H_{c2}: Probe for multiband superconductivity - applicable to bulk and interface



- SF density and H_{c2} are complimentary probes



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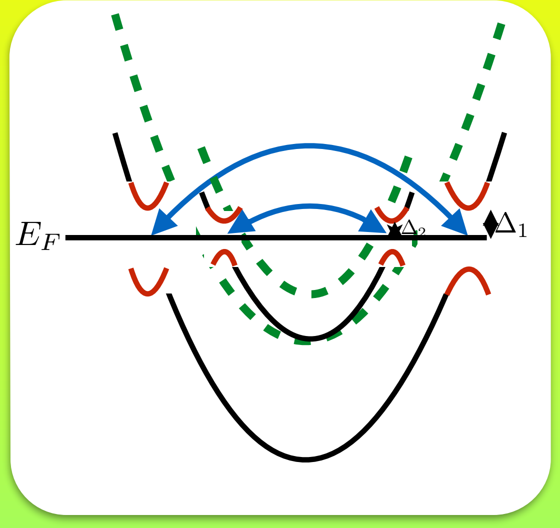

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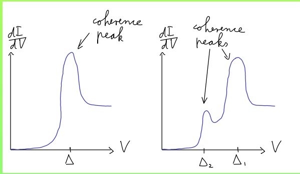

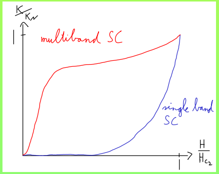

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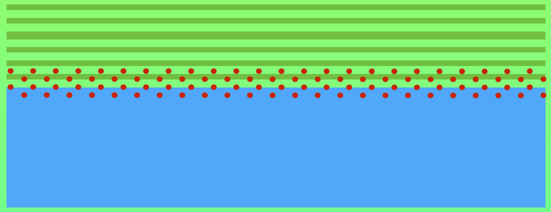

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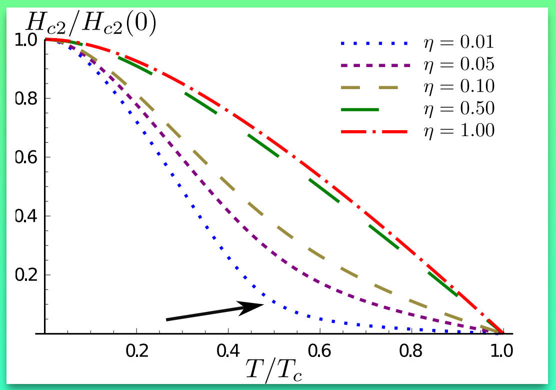
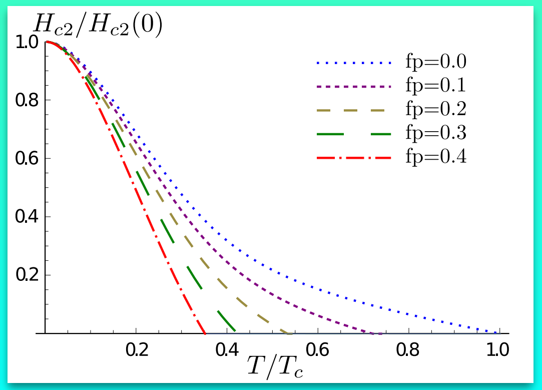


- SF density and H_{c2} are complimentary probes



Thank you!